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**BUILDING SCIENCE**  
**FOR STUDENTS OF ARCHITECTURE**  
**AND BUILDING**



# BUILDING SCIENCE

FOR STUDENTS OF  
ARCHITECTURE AND BUILDING

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## VOLUME I

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*By*

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## PREFACE



THE importance of science in architectural education is slowly receiving full recognition. We have evidence, increasing every day, of the ways in which the use of more recently developed materials and constructional methods—structural steels, reinforced concrete, “plastics,” built-up wood products, metals and the like—is inevitably leading to a new architectural “style” for the types of building in which they are used. The responsibility for this belongs only indirectly to the architect. The labours of the scientist, and the results, are under present-day conditions taking the place of many generations of patient trial and error in the selection and use of materials, both those largely untried and also those well-tried under older conditions but now in many cases put to newer uses.

Much research has been done in the past quarter century in this and other countries, and there is now available a great and growing accumulation of literature dealing with matters of vital importance to architects and builders. So far as this country is concerned most of this work is done at the Building Research Station at Garston, near Watford, Herts, the Building Research Board responsible being appointed by H.M. Department of Scientific and Industrial Research, and in lesser degree at the Forest Products Research Station. The results of their work are freely published and there is thus no lack of special scientific information available; nevertheless the busy architect or builder can hardly be expected to spend a lot of time and energy in becoming familiar with it. In fact the “casual relations between Building research and Building practice” (to quote a recent Report of an Architectural Education Committee) finds no parallel in other important industries. The solution of this problem appears to be insistence upon a more scientific bias to instruction in architectural courses, not only in advanced technical subjects but right from the commencement. Most purely Building courses, free from the claims of æsthetic aspects, have long devoted much

time to applied science and mathematics. Again quoting from the Report, the architect of the future should be "in a position to appreciate and to utilize the results of scientific investigation and be better able to judge rightly between the competing claims of alternative schemes submitted by specialists and consultants."

The few existing books on Building Science, though excellent, vary considerably in their arrangement and scope, and it is frequently found that no particular one covers the exact ground required for a particular course. It is most important that the approach to all aspects of Building Science should be experimental. It is much better for the student to be taught how to study a textbook for himself than to have one dictated to him in class. Building Science is not a "lecture" subject and this means that he must have access to a suitably equipped laboratory. Further, to make the most of such facilities, the practical work should be so arranged as to lead directly to the deduction, on the part of the student himself, of principles—rather than principles be taught and experimental work done merely as a check.

Building Science should obviously be closely related throughout to Building Construction, and it is the writer's opinion that both should be taught by the same instructor. No amount of collaboration between two individuals can quite achieve this object, especially as the one is frequently a science master with little or no experience of the Building industry whilst the other is invariably a trained architect with subsequently acquired skill in teaching.

This book was mainly prepared long before the publication of the Report previously mentioned but was identical in scope with the recommended treatment, and only slight re-arrangement has been necessary to bring it completely into line. The syllabus is divided into three main Sections as follows :—

I.—**MATERIALS.** (The science underlying the use of constructional materials and their exposure in the fabric of buildings.)

II.—**STRUCTURES.** (The science underlying the structure of buildings and the strength of structural materials.)

III.—EQUIPMENT. (The science underlying the equipment and occupancy of buildings.)

In this volume sufficient elementary work has been included in each of these Sections to make the treatment self-contained, but an endeavour has been made to keep to fundamentals in this respect.

Whilst primarily intended for the use of architectural students, this book will also be of service to students of the allied professions, and more than covers the scope of the vast majority of courses leading to the National Diplomas and Certificates in Building. It will also be found to contain suitable elementary material for the science classes in Junior Technical Schools of Building.

The writer would have liked to acknowledge all the sources of information he has tapped in the preparation of this work. These have been so many and varied, however, that this is impossible, especially if account is taken of a practical experience—extending over a quarter of a century—in architectural practice and teaching. The short bibliography given at the end includes those published works most likely to be of use for further study.

In conclusion, acknowledgment must be made of the valuable help given by the writer's colleague, Mr. A. J. Eales, B.Sc.Eng., in checking the manuscript.

ALFRED G. GEESON.

*Wolverhampton.*



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# SECTION I—MATERIALS

## CHAPTER I

### MATTER

1. *Structure of Matter.*
2. *Forms of Matter.*
3. *Properties of Matter.*
4. *Other Forms of Matter and their Properties.*
5. *Structure of Solids.*

#### 1. STRUCTURE OF MATTER.

All substance or *matter* may readily be distinguished in that it occupies space ; heat, sound, force etc. do not occupy space. These are forms of *energy*, not matter, although one hears such loose phraseology as a " heat-storage " vessel or a " volume of sound."

**Atoms and Molecules.**—A stick of chalk is composed of a great number of small pieces or grains as is apparent when we write upon a blackboard with it—so small that they float about in the air. If we place one of these grains on a hard surface and press upon it with the blade of a knife we find we can crush it into still finer particles. If we could separate out one of these (we might have to use a lens or even a microscope in order to see it) it is easy to imagine that, given sufficiently fine mechanical means, we could reduce it to even still smaller particles. It is also not difficult to imagine the whole process repeated time after time until the minute particles of chalk simply could not be further subdivided, even in imagination. This ultimate particle of chalk, the unit of which the stick is built up, is called a *molecule* of chalk. It is obviously not visible, even with the aid of the most powerful microscope.

Now chalk, although a convenient substance to illustrate this point, happens to be a compound substance—in brief it is produced from several other simpler, elemental substances. If instead of the stick of chalk we could have used a piece of the metal calcium, or pure carbon, or a quantity of oxygen gas—all of which are " simple " substances—our ultimate particle would have been an *atom*.

From this it would appear that the molecule can, after all, be considered capable of still further division. This is true *but* these further subdivisions are no longer particles of chalk but the ultimate particles or atoms of the substances which have combined to make up the chalk—viz. calcium, carbon and oxygen. The molecule of chalk consists of one atom of calcium, one of carbon and three of oxygen, combined in a certain way which will be elucidated shortly.

In order to build up a solid wall out of a heap of loose bricks we have to arrange the bricks in some sort of order and place between them mortar to bind them solidly together. In a somewhat similar manner the atoms comprising a quantity of matter are kept in position relative to each other by what might be termed a "spacing agent," in this case force. This *inter-atomic force* is an attraction which adjacent atoms exert upon each other, and the intensity of which depends upon their closeness to each other. Actually the force uniting atoms is known to vary inversely as the square of the distance between them—in other words if we could double their distance apart the inter-atomic force would be reduced to one quarter; at three times the distance the force would be one-ninth; at half the distance it would be four times as great, and so on. But as we shall see when considering the structure of solids in more detail there is a minimum limit to this inter-atomic distance—when the atoms come sufficiently close to each other they are kept at that distance, and if they are pushed closer the force is reversed and they repel each other to this limiting distance. The inter-atomic distance is different in different types of matter and in different states of the matter, but this will be discussed more fully later.

To illustrate the arrangement of atoms we sometimes draw a diagram showing blobs or circles distanced by straight lines, the blobs representing the atoms and the lines the forces between them. Models are available for the same purpose in which balls and wires are used. We must, however, always think of them as the smallest imaginable particles without definite area or surface.

As we have seen in the case of chalk, it is not only atoms of the same substance that attract each other. When atoms of different substances gather together they may constitute a molecule of a new substance, and in doing so a certain portion of their inter-atomic force is brought into play. This used portion we call chemical attraction or *chemical affinity*, but always there remains sufficient to draw and hold the molecules together, and this is termed the force of *cohesion*. Cohesion is more important to us at the moment than chemical affinity.

**THE ATOMIC THEORY.**—The atomic theory of matter was put forward in 1808 and has so far worked so well that, in spite of more recent discoveries any different views of the constitution of matter brought about by such progress makes little difference to the conception of the atom in chemistry.

Various theories have been formulated at different times to account for the nature of electricity, the one accepted at present being what is known as the atomic or electron theory. According to this theory the atom comprises a nucleus around which revolve at enormous speed other

“ particles ” called electrons. A current of electricity is a collection of these electrons separated from the nuclei and allowed to pass from atom to atom through a conducting material. It will be seen that this idea of the atom in no way challenges our conception of it as being the smallest particle of elementary substance, *i.e.* the particle which can suffer no further subdivision in chemical action.

## 2. FORMS OF MATTER.

Under normal conditions matter is either *gas*, *liquid* or *solid*. This is a broad classification for we know that some substances exhibit properties which appear to be intermediate between those of a liquid and a solid, whilst granular solids act in certain ways like liquids.

**Gases.**—Generally speaking we may say that in a gas or vapour the particles are comparatively widely separated and the inter-atomic force so weak as to be inoperative. A gas therefore does not “ hold together ” but flows and readily disperses in all directions.

**Liquids.**—The particles of a liquid are much more intimately associated than this and the inter-atomic force is greater. A liquid therefore does “ hold together ” but the force is still not of sufficient intensity to prevent outward flowing due to its weight. A containing vessel is therefore necessary to enclose a certain quantity of liquid.

**Solids.**—The average solid is quite different, assuming a rigid form which shows that the particles are very closely spaced and held by such inter-atomic force as to prevent visible flowing. To such extent is this so that in some cases, *e.g.* iron, we have to apply very great force to it in order to alter its shape very slightly.

This classification applies, as stated, to different substances under normal conditions, but by altering the conditions we can in many cases make the same substance assume different states. Water is perhaps the first example to come readily to mind, capable of existing as gas, liquid or solid according to its temperature and pressure.

We have seen how in chemical action atoms may combine to form molecules. The vast majority of substances are composed of molecules, even some which comprise one kind of atom only, *i.e.* elementary substances, but it is the force of cohesion which decides which of the three forms—gas, liquid or solid—the substance will assume under given conditions.

**Heat Motion.**—When we come to study the nature of heat we shall find that it has a great bearing upon the structure of matter ; for the moment it will suffice to say that what we call heat is energy produced by vibratory motion of atoms and molecules—not to be confused with the

motion of the electrons within the atom. Under the conditions prevailing on this planet the atoms are never entirely free from vibration, *i.e.* they are never absolutely cold. In a general way we know that freezing water is a good deal colder than boiling water ; water—or ice—in a state of complete freedom from heat motion would be about  $2\frac{1}{2}$  times colder still.

Ice is a compact solid in which the molecules are arranged in a rigid mass so that each can move only very slightly, the force of cohesion even near melting temperature not permitting flow to take place. At melting temperature the heat motion receives a sudden impulse, but not sufficient entirely to overcome cohesion, and the ice becomes water. From this point heat motion increases until at boiling temperature under another impetus it becomes so vigorous as practically to destroy cohesion, and steam is formed. Throughout this range no chemical change has resulted from this progressive weakening of inter-atomic force.

### 3. PROPERTIES OF MATTER.

We have defined matter as that which occupies space. A piece or aggregation of matter is called a *body*, and the amount of space which it occupies is its *volume* (quite distinct from its shape).

A body of gas has no definite shape, size or volume (unless enclosed).

A body of liquid has no definite shape but has definite size or volume.

A solid body has definite shape and definite size or volume.

**Properties of Gases.**—A gas is *compressible*. By exerting pressure on a gas we can make it occupy less space ; this is easily verified in the operation of inflating a tyre. Most gases can be compressed to an enormous extent, and this is what might be expected from our previous remarks as to their structure, although if continued there comes a point at which they liquify. Some of the gases used in science and industry and which are transported in metal cylinders are really liquid under the terrific pressure under which they are stored, turning to gas again on being reduced to the lower pressures at which they are used. Air liquifies when its volume has been reduced to roughly  $\frac{1}{800}$ .

A gas is *elastic*. If we release a gas from confinement in an enclosed space into a larger space hitherto empty it expands so as to fill the space completely and exerts pressure on the bounding surfaces ; it becomes more attenuated in the process of course. A gas never has a free surface like the upper surface of a liquid or the face of a solid.

If we release the gas into a vessel or enclosed space occupied by another gas they gradually merge into a uniform mixture. This property is known as *diffusion*, and the gases are said to be *miscible*. Even if one of the gases is much " heavier " than the other, diffusion takes place rather than the two forming distinct layers. A very slight leak of coal

gas in a room is almost immediately noticeable in any part of the room. Only on a very large scale, as in nature, is this phenomenon not always observed, and then we get the "heavy" gases separating by their weight from "lighter" ones. For instance our atmosphere varies in composition the higher we go until ultimately at a height of many miles hydrogen begins to take the place of air.

We have seen earlier how easily gases flow, the particles being free to move relative to each other with negligible friction. Different gases vary only slightly in this respect and in all cases flow very much more readily than the most easy-flowing liquid.

**Properties of Liquids.**—A liquid is obviously "heavier" than a gas since more particles are contained in a given volume, and it flows less readily owing to greater internal friction.

A liquid also responds less readily to pressure; the particles are so much more close together that it takes a great force to compact them any more. In fact for practical purposes a liquid can be considered to be *incompressible*.

**EXPERIMENT 1.**—To show the incompressibility of water.

Take a flask or bottle, completely fill it with water, and try to push a cork into the neck to seal it. We cannot do so as it is impossible to squeeze the water into a smaller volume.

Next pour out a very small quantity of the water and try again to push in the cork. This time the cork goes in, but immediately we release our hold on it out it comes again. This shows the elasticity of the small amount of air left in the top of the bottle.

Liquids which are miscible also diffuse like gases and so appear to defy the law of gravity, whilst a gas may also diffuse into a liquid with which it is in contact.

Gases and liquids are similar in the sense of being able to flow so they are classed together as *fluids*. We shall see later that certain solids in a state of fine division, such as a heap of sand or a silo full of grain, can also for certain practical purposes be included. In a certain type of cement testing machine the force is applied gradually to the specimen by running water through a tap from one vessel into another. Other machines of the same type use fine lead shot in an exactly similar way; this is just as effective and more convenient.

Certain other important properties of gases and liquids will emerge in later chapters where we can more conveniently relate them to practice.

**Properties of Solids.**—A solid is perhaps most readily distinguishable from a liquid or a gas by the way in which it retains its shape. It does not appear to flow under its own weight, and usually withstands



considerable applied force without being visibly affected. This property is referred to broadly as *strength*.

Although a solid does not flow of its own accord we can change its shape if we apply sufficient force to it. The question of compressibility of a solid needs some explanation. We have seen that a liquid is almost incompressible and we ought therefore to expect a solid to be more incompressible still. Under identical conditions this is so, that is if the solid is enclosed in a strong tightly-fitting container (unless the solid is porous, when it will compress owing to the air spaces in it offering no resistance). In practice a liquid must be contained whilst a solid is not. What happens can be seen if we take a block of soft material like glaziers' putty or plasticene and press something flat and hard on top of it. The block is reduced in height, but only because at the same time it has bulged or increased in width. If we packed the putty into a cylinder and applied an identical force by means of a piston we should not get this shortening.

When we say, then, that solids vary in their degree of compressibility we are really using the term in a rather different sense than when referring to liquids.

Let us see what may happen when we apply a continuously increasing pressure to a solid in the form of a free block. If it should be a block of chalk we shall find that it will crush into a heap of grains almost immediately ; a block of building stone will do the same only it will take longer ; a block of lead will squeeze out without falling in fragments or splitting ; a block of rubber will do the same ; a block of cast iron will bulge considerably but will then split ; a block of steel will bulge but will not split so soon.

Let us next apply a moderate force, afterwards removing it, then a stronger force, removing that, and so on in stages. The chalk will probably crush down the first time ; adhesion is not very great and the chalk is said to be *divisible*. After the first stage the stone will probably have regained its original height, but soon the sides will show signs of cracking and bursting off. The lead will have shortened and bulged considerably and will stay in that condition ; further increments of force merely increase the shortening and bulging. The lead is therefore *plastic*, and also because it does not crack or split after many stages of loading it is said to be *tough*. The rubber will squeeze out like the lead, but after removing the pressure it will be found to have regained its original height and breadth ; it will still do this after repeated application and removal of the pressure and is therefore said to be *elastic*. Because it does not crack or break it is also tough. (The term "elastic" has come in for abuse in common parlance and is often used as an alternative name for rubber. The word is an adjective, as is the term "plastic" this also

nowadays tending to be used as a loose abbreviation for "plastic material.") The cast iron will resume its shape for a time, possibly after two or three stages, but then the shortening and bulging will become permanent and without further warning it will crack. It is thus *brittle*. The steel (the kind of steel used in building is "mild" steel) will withstand quite a number of stages, each time returning to its former shape, but then deforms permanently and does not quite return. This increases slowly until it, too, breaks, showing that steel is only moderately elastic and moderately tough or ductile, a combination of properties valuable in the uses to which building steel is put.

*Hardness* is a term applied to a solid which relates to its power to resist surface deformation such as scoring and denting. A diamond is well known to be harder than glass and is used for the purpose of scratching or "cutting" it.

#### 4. OTHER FORMS OF MATTER AND THEIR PROPERTIES.

**Condensed Vapours.**—A vapour differs from a gas only in degree and from our point of view the terms are synonymous. We usually term "gas" a substance which is gaseous at ordinary temperatures, and "vapour" one which is liquid or solid under normal conditions. The white cloud issuing from a glass vessel in which water is boiling is sometimes loosely referred to as steam. Steam is, of course, a vapour and is invisible, since it cannot be seen inside the vessel, only becoming visible after condensation in the cooler outside air. It is then an extremely finely-divided liquid. These condensed vapours should not be confused with smokes.

**Semi-Solids.**—Some fluids flow very readily whilst others appear to have difficulty in doing so, compare water and engine oil in this respect. The oil is said to be *viscous*, and its comparative reluctance to flow is called its *viscosity*. At ordinary temperatures paraffin wax is a solid, but upon being heated it gradually becomes plastic, then viscous, then liquid and finally vapour. All these states may be observed in the case of a burning wax candle.

The *plastic* state may be considered intermediate between viscous and solid.

Pitch, bitumen and asphalt are well-known examples of semi-solids. They have no definite melting temperature but become gradually viscous as heat is applied.

A lump of coal tar pitch appears on inspection to be an obvious solid; it is rigid and hard, and splinters when broken. Yet at ordinary temperatures it slowly flows, very slowly it is true, until it has assumed

the shape of a containing vessel. It is obviously an extremely viscous liquid, and appears to have no intermediate plastic state.

Bitumen is a black substance resembling pitch in appearance. It occurs naturally in springs and pools in the region of the rivers Tigris and Euphrates and was used as a mortar in early historical periods.

Asphalt is natural bitumen containing fine clay and other mineral impurities. In Trinidad is a pool or lake of this material which is cut out in blocks much as stone is quarried. Nevertheless unless work in one part is continuous the pool preserves its level surface on account of its viscosity. It is refined before export and is the form of bitumen mostly used in the manufacture of the best quality bituminous products, such as bituminous felts, D.P.C.s, paints, etc.

Rock asphalt is a natural formation of bitumen-impregnated limestone. Such formations occur in many parts of central Europe. The proportion of bitumen is generally very much lower than in the case of lake asphalt, and has to be increased by the addition of more bitumen in the preparation of mastic for roofing, waterproofing, etc. For such work the material is heated, applied hot by spreading, afterwards being consolidated, so conforming closely to irregularities in the surface to which it is applied. In this state it is not adversely affected by subsequent small movements of the work. Inferior materials for these purposes are made from oil pitches and crushed stone.

Asphalt should not be confused with "tarmacadam" such as is used for paving. This consists of limestone chips coated with coal tar and consolidated by rolling.

**Solutions.**—So great is the affinity of different types of atoms for each other that very few elementary substances are found in nature. Most natural solids are either compound materials like chalk or more often extremely complicated mixtures of different compound materials. These mixtures are mixtures of tangible particles such as grains of sand with grains of lime, but in a solution we have a *mixture of molecules* of different substances uniformly distributed.

**SOLUTIONS OF GASES.**—Take the case of two different gases. Each has no cohesion and the atoms or molecules of one readily intermingle with those of the other in any proportions. The two gases are said to *dissolve* in each other or to be mutually *soluble*, and the result is a *solution*, although in the case of gases it is more often referred to as a *mixture*.

**SOLUTIONS OF LIQUIDS.**—If we consider liquids we find that, unlike gases, pairs of them do not necessarily dissolve. Some pairs such as water and alcohol, or oil and alcohol dissolve in any proportions like gases. Others partly dissolve, whilst water and oil do not dissolve at all.

**EXPERIMENT 2.**—Place two measuring vessels side by side, both containing equal amounts of water. Take smaller equal quantities of (a) paraffin and (b) alcohol in different vessels and add one to each of the vessels containing water. Stir both and read off the combined volume in each case.

**SOLUTIONS OF SOLIDS.**—Solids obviously cannot be mutually soluble since the force of cohesion is so great, but some metals are formed by the mutual solution in a liquid state of other metals. Brass, for instance, is the solidified form of a solution of liquid copper and liquid zinc, and is an example of an *alloy*. Bronze is similarly formed from copper and tin.

**SOLUTIONS OF GASES AND LIQUIDS.**—When we consider a gas and a liquid we find great differences in behaviour. For instance hydrogen chloride is a gas which dissolves in water to such an extent as to produce a solution (hydrochloric acid) in which the proportions are about one-third hydrogen chloride and two-thirds water. Gases like carbon dioxide (carbonic acid gas) are not nearly so soluble in water as this, whilst oxygen is only very slightly soluble.

The amount of gas that can be held in a solution is reduced by raising its temperature. Carbon dioxide is released from water in which it is dissolved by the process of boiling, as we shall see when studying natural water.

The amount of gas that can be held in a solution is also reduced by decreasing the pressure acting on it. Thus soda water, which is a solution of carbon dioxide in water at high pressure, gives up some of the gas in the form of bubbles when the pressure is reduced by operating the syphon.

**SOLUTIONS OF LIQUIDS AND SOLIDS.**—When we speak of a solution in everyday life we usually refer to a solution of a solid in a liquid, and

this kind of solution is of most importance in connection with building. In these cases the liquid is termed the *solvent* and the solid the *solute*. Although water is by no means the only solvent it is the principal one and the one with which we shall be most concerned in our study of building problems.

For a solid to be able to pass into solution it must be one of the type having a crystalline structure, *i.e.* one composed of crystals. This type of solid is investigated more fully in the next section, "Structure of Solids," but for the moment it

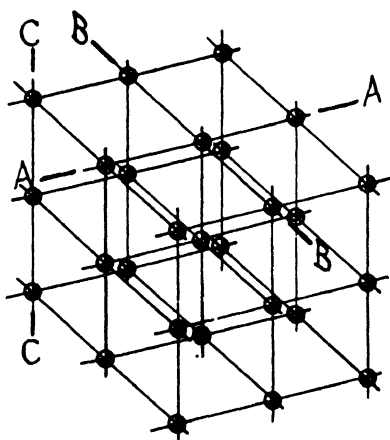


FIG. 1.—Arrangement of Molecules in Cubic Lattice.

is necessary to understand the meaning of the term. A solid is crystalline when its atoms or molecules are arranged in relation to each other in some regular order or pattern. For instance one type of solid of which common salt is an example, has its molecules arranged equidistant from each other in three perpendicular directions as in Fig. 1. If we look carefully at this diagram we can distinguish the "unit" of the pattern in each direction to be a square, and the "unit" of 3-dimensional pattern to be a cube. The arrangement or pattern is called a *lattice*, and if the crystals are of a substance which is soluble, what happens is that the attraction between the molecules of the solvent and those of the solute is so great as to cause the latter to break away from the lattice formation and mix freely with the others.

*Saturation.*—The solid is now in a molten state and is therefore liquid like the solvent, but there is a limit to the extent to which this can occur. When this limit is reached the solution is said to be *saturated*, and any excess of the solid remains in an undissolved state. By raising the temperature, however, we increase the heat motion of the molecules and as might be expected more of the undissolved solute is enabled to pass into solution. This is the general rule but as with many other rules there are a few exceptions; in this case we find that amongst other substances lime and common salt hesitate to comply. The solubility of common salt, for instance, in cold water is increased by less than 4 per cent. with boiling water, whilst with some other substances it may increase up to 50 per cent. over a quarter of this temperature range.

If we reduce the temperature of a saturated solution some of the solute regains its crystalline form, although the solution remains saturated. There is thus in each case a relation between the maximum amount of solid held in solution and the temperature of the solution.

Crystallization from a cooling solution does not always occur at the moment when saturation point is reached. There is sometimes an apparent disinclination, which is however overcome immediately a crystal of the same substance is introduced.

**EXPERIMENT 3.**—Dissolve powdered alum in warm water until a saturated solution is obtained. Allow to cool and then lower gently into the solution a single crystal of alum suspended from a hair or fine thread. Crystallization is observed to commence on the surfaces of the crystal and to increase rapidly. The best result is obtained when the solution is kept absolutely free from vibration and away from draughts of air.

*Supersaturation.*—A solution which for any reason is more than saturated, *i.e.* one which contains more solute than normally required to produce saturation, is termed a *supersaturated* solution. In such a

solution the excess of solute is always tending to crystallize, and the solution is thus *unstable*.

**EXPERIMENT 4.**—Prepare a hot saturated solution of sodium sulphate, pour on top a thin layer of oil, and allow to cool. The solution is now super-saturated and no crystallization will take place until the film of oil is broken, as by a glass rod, when crystallization is instantaneous.

**EXPERIMENT 5.**—Take a round-bottom flask fitted with a rubber bung through which passes a short length of glass tubing. To this attach a rubber tube about two inches long with a clip or pinchcock as shown in Fig. 2. Put into the flask a hot saturated solution of sodium sulphate and, *with the clip removed*, boil it until steam issues from the rubber tube. This has the effect of driving out the air contained in the top of the flask. Whilst steam is issuing freely remove the source of heat and immediately close the clip, then allow the solution to cool. No crystallization occurs until the clip is opened and air admitted to the flask, but it then occurs instantaneously.

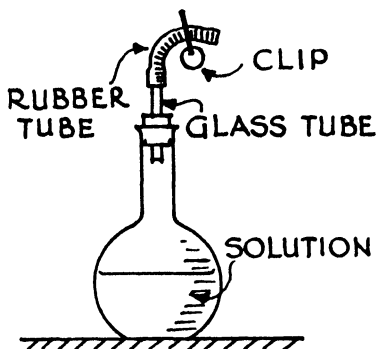


FIG. 2.—Instantaneous Crystallization.

**EXPERIMENT 6.**—Prepare a saturated solution of sodium thiosulphate (sometimes called sodium hyposulphite or "hypo" by photographers) and warm water and pour it into a warm beaker. (A in Fig. 3.) Next prepare a warm saturated solution of sodium acetate and pour slowly on to

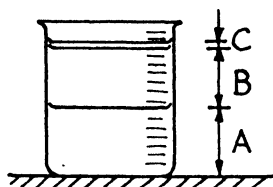


FIG. 3.  
Selective Crystallization.

the first solution. (B in Fig. 3.) Add to this a little boiling water. (C in Fig. 3.) Let the whole cool slowly. Then take a single hypo crystal on the end of a thread and lower it gently into the beaker. It will be observed to pass through solution B without incident but on reaching solution A the latter immediately crystallizes. Next take a single sodium acetate crystal on a thread and lower it; the solution B will follow suit.

**Osmosis.**—We have seen that a gas confined in a vessel exerts pressure on the inner surfaces of the vessel. The molecules of solute and solvent in a solution exert pressure in the solution, quite distinct from that due to the liquid on the sides of the vessel. This is called *osmotic pressure* or *osmosis*, and it has been suggested that the disintegration of brickwork and stonework may be partly due to osmotic pressure of dissolved substances in the water with which the work is saturated. Whilst the truth of this is doubted by some authorities it is interesting to observe its effects upon a thin membrane.

**EXPERIMENT 7.**—Take a toy balloon of thin rubber and fill it with a strong solution of sugar, afterwards tying up the neck securely with thread or a strand of wool. Lower into a vessel containing a weaker solution and suspend it there. After a time, depending on the difference in

strength of the two solutions, the balloon is seen to have swollen because the pressure on the inside of the balloon is greater than that on the outside surface. If the balloon is dipped into pure water, i.e. solvent without any solute, the distention of the balloon will be much greater. The difference in pressure is caused by the water or weak solution diffusing inwards through the rubber faster than the strong solution diffuses outwards.

**Colloids.**—It has been noted that matter can exist as gas, liquid, various kinds of solid, and solution. There is a further important way in which molecules group themselves together so as to act as a building-up unit of certain types of substance.

How, for instance, are we to classify things like glue, smoke, meat or wool? The group of substances of which these are common examples is known as *colloid* and they are built up of colloidal particles. They consist of molecules of solid or liquid associated with, or dispersed in, a fluid which may be gas or liquid. The two, that is the particle and the medium, must of course be mutually insoluble and not able to combine chemically.

**SMOKES AND SUSPENSIONS.**—Smoke consists of solid particles of carbon in suspension in the air. These might, in still air, be expected to sink to the ground or to the bottom of the containing vessel of their own weight. The larger particles do fall after a time, but the smallest particles exhibit a striking persistence in remaining suspended in the air. They are prevented from coagulating and so enabled to remain in suspension for a long time by a mechanical force known as Brownian movement, but differ from a gas in that they will all ultimately settle in the form of a very fine dust.

**EXPERIMENT 8.**—To show the gravitation of smoke particles.

Take a clean gas jar and fill it with a dense smoke. The easiest way to do this (although not an approved laboratory method) is to fill the mouth with tobacco smoke and then apply the mouth to the jar as though to drink, but keeping the jar in an almost vertical position. Blow the smoke into the jar very, very gently. This may require some practice, but if successful the smoke will pour into the jar somewhat like a liquid and displace the air. When sufficient is in the jar take another clean jar and, putting the rim of the first

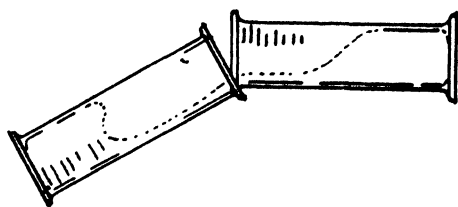


FIG. 4.—Pouring Smoke from a Jar.

inside, and in contact with, the inside of the second jar, pour the smoke from one jar to the other as shown in Fig. 4. This may appear rather surprising at first as the smoke pours rather like a liquid, the reason being that owing to the rim of one jar being inside the other jar no current of air is allowed to come between them and so disperse the smoke.

Having collected the smoke in the second jar cover it with a ground glass cover and place aside. After a few minutes the smoke will be observed, by the gradation in density or colour, to have commenced to settle. It will not be until some hours have elapsed, however, that no smoke at all can be perceived in the upper part of the jar. If the jar be left undisturbed for a week and the cover then removed, a thin coating will be seen to cover the bottom like "smoked" glass; this will be more readily apparent if part of the film is wiped off.

**EXPERIMENT 9.**—To separate a solid from suspension in liquid.

To a test-tube half full of water add a little red lead or flowers of sulphur and shake vigorously, having closed the mouth of the tube with the thumb. Then stand the tube in a rack or elsewhere so that it is free from movement. These substances are finely divided solids and any larger particles will soon settle to the bottom, but it will be a long time before no colouring remains in the upper part of the water. It is best to view the tube with a sheet of white paper behind it. The substance will, however, all settle ultimately and is really a smoke in a liquid instead of in a gas.

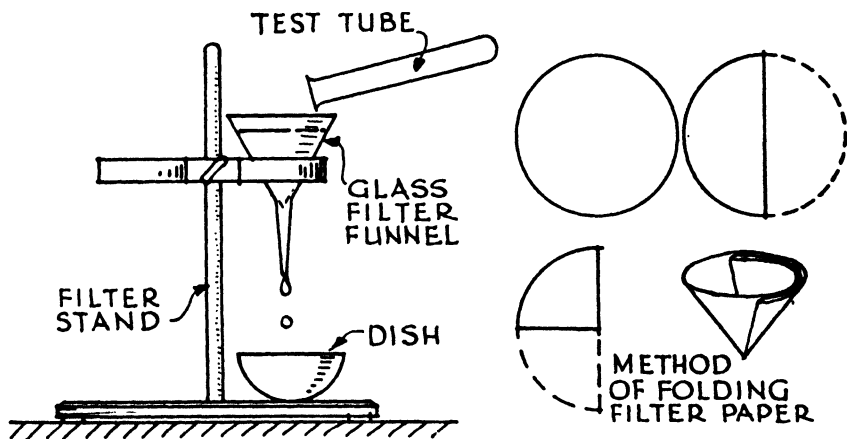


FIG. 5.—Filtering a "Suspended" Solid.

To show that it is merely in suspension and not in solution it may be shaken up again and passed through a filter paper (Fig. 5), being careful not to fill the funnel higher than the top of the filter paper. The substance will all be retained on the paper and the liquid which filters through (called the *filtrate*) will be found to be clear water.

These smokes are examples of solid colloidal particles in gaseous and liquid media.

**EMULSIONS.**—Another example of common occurrence is what is known as an *emulsion*. This is composed of particles of oily liquid



suspended in water or other non-oily medium, and may also be classed as a smoke. Milk is a natural example.

**EXPERIMENT 10.**—To prepare an emulsion.

Add a few drops of any oil to water in a test tube and shake fairly vigorously. The oil will be seen to have separated into minute globules which only coalesce into larger drops after some time. Shake more vigorously and the oil will separate so finely as to give a general cloudy appearance to the water; it will also take a much longer time to coalesce.

Natural suspensions and emulsions have their colloidal particles much more finely divided than we can hope to achieve by merely pulverizing a solid or shaking a liquid, and are therefore much more stable. Although cream rises to the top of milk it by no means represents the whole of the fat in the milk.

**GELS.**—The examples of colloids so far considered are instances in which the colloid particles are free-moving. In gelatin and glues they are less free to move, whilst in animal and plant fibres (meat, wool, cotton, timber, etc.) they form a more rigid structure still.

Gelatin and glue can be considered as colloidal matter in solution; in strong solution they are extremely viscous, almost solid, but by adding more solvent (water) they naturally become less so. Vegetable fibres, as in timber, are formed by the natural drying of colloidal solutions, the sap.

These stiffer colloids like glue and timber are called *gels* and as they result from the drying out and consequent shrinking of colloidal solutions they exhibit the property of swelling once more upon coming into contact with water. This fact is of great significance in building construction since not only timber but materials like stone, brick, concrete and mortar have the same peculiarity, although to a limited extent. Gels and the moisture movement of timber are dealt with further in Chapter IV.

## 5. STRUCTURE OF SOLIDS.

We have already considered the chief points of difference between the various forms of matter, and have seen how atoms are held together in the simple substances called elements, and how different kinds of atoms combine chemically to form molecules of other substances. We have seen, too, how molecules of different kinds become associated in mixtures or solutions and in colloidal particles. We must now consider in more detail the make-up of solid matter, for although the other forms of matter are important to us in their effects on building materials and in questions affecting the use of buildings, the materials themselves are solids.

**Crystalline Solids.**—In the first instance solid matter resulted from the congealing or setting of liquid matter ; the metals and igneous stones such as granite are examples. Materials like sandstones and limestones arose by subsequent erosion and deposition, together with natural pressure, or heat, or chemical action or biological processes. Certain other building materials are manufactured—bricks, concrete, window glass, etc. For the moment we are concerned with the process of formation directly from the liquid state.

**CRYSTALLIZATION FROM MELT.**—When a normally solid substance (with a few exceptions) cools from a molten state the heat motion of the atoms or molecules is gradually slowed down until, just before solidification occurs, they arrange themselves in lattice formation as already explained. The unit of the lattice is the single crystal which is a grouping in formation of a number of molecules. This is still another way in which they become associated to form a structural unit of matter.

**EXPERIMENT 11.**—To prepare crystals from a melt.

Fill a crucible or a porcelain fireproof basin with flowers of sulphur and heat it so that it melts without igniting. This is best assured by covering the basin with a special lid—a pair of crucible tongs should be used for this purpose. When the sulphur has all melted remove the burner and the lid and allow the melt to cool. After a

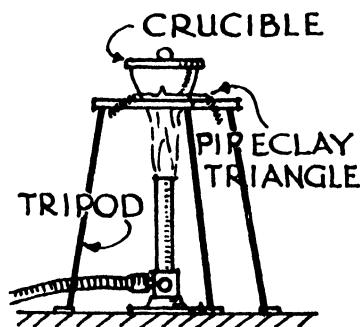


FIG. 6.  
Crystallization from a Melt.

time a thin crust will be observed to form on the surface ; at this stage pierce it and pour away into a vessel of cold water the still liquid sulphur below. Then break open the crust and examine the inside of the basin. Around the sides, and also projecting from the underside of the crust, will be seen brown transparent needle crystals of sulphur. These are "monoclinic" crystals. Put the basin aside for a week and then examine the crystals afresh. They will still be of the same shape and size, but will be of a lighter colour and no longer transparent. Each has separated into smaller crystals of a different shape (octahedral crystals).

Although sulphur is not a building material its manner of solidifying by crystallization is exactly similar to that of the metals. Experiment 11 can conveniently be repeated with tin or lead, using a small crucible, but the crystals of metals are imperfectly formed because during their growth they impede each other so that we do not see the true crystal shapes. If we wish to examine metallic crystals it is better to reverse the process as in the next experiment, or to utilize chemical action as in Experiments 13 and 14.

**EXPERIMENT 12.**—To demonstrate the crystalline structure of metals.

Take a stick of pure tin, such as is used by plumbers to "correct" their solder, or a short bar of lead (a 9-in. length of  $\frac{1}{4}$ -in. lead water pipe is suitable) and heat it gently in the centre in a small bunsen flame. Keep the bar turning and moving so as to spread the heat fairly uniformly over a few inches of its length, and whilst doing so exert a slight bending action. To do this hold one end in each hand using cloths to avoid burns. When the metal is just about to melt—it may have melted slightly on the surface—the bar will break quite readily. Remove from the flame just as breakage appears imminent so as to avoid contact between it and the fractured surfaces, and when sufficiently cool cut with a sharp penknife a thin slice from a fractured end. Place this under a magnifier or a low-power microscope and examine the crystalline structure. Although the crystals are quite soft they exhibit all the appearances we associate with those of the more brittle substances.

**EXPERIMENT 13.**—To produce "free" crystals of lead.

Make a small hole through the bung of a wide-necked glass jar and fit into it the ends of a bunch of thin brass or zinc wires. Nearly fill the jar with a solution of lead acetate in water. Introduce the wires into the solution as in Fig. 7, secure the bung, stand the

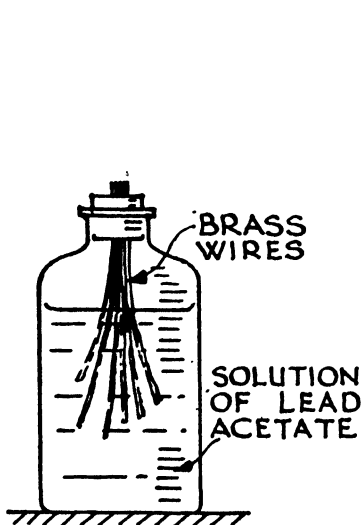


FIG. 7.  
Preparation of Lead Crystals.

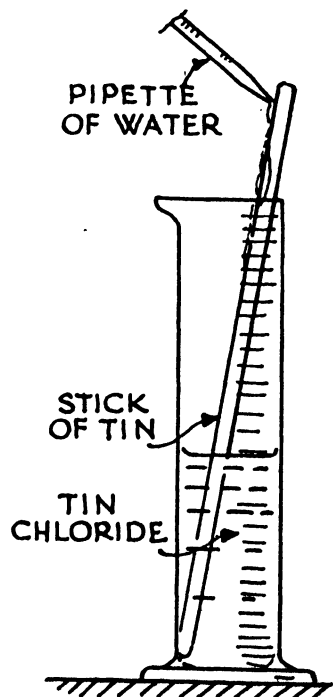


FIG. 8.  
Preparation of Tin Crystals

jar aside, and note the formation of crystals of lead along the wires. These will increase in size until the wires present a spangled appearance

**EXPERIMENT 14.**—To produce "free" crystals of tin.

The materials and apparatus required for this experiment are :— a small pipette, a tall glass jar such as a graduated cylinder, a stick of tin and some tin chloride.

To prepare the tin chloride scrape some thin shavings of tin into a beaker containing hydrochloric acid until no further bubbling occurs. Pour off the clear liquid into the jar so as to fill it to a quarter or a third of its height, and introduce the stick of tin as illustrated in Fig. 8. Now, from the pipette (*see* Chapter II) allow drops of water to trickle slowly down the tin, and after a time crystals of tin will be observed to form around its sides.

Crystals of zinc are much in evidence on the surfaces of galvanized steel articles, and owing to the small thickness of the coating they usually assume much the same shapes as frozen rain on a window pane. Scientific instruments are also sometimes seen with their iron parts protected by a special finish consisting of a coating of crystals.

**CRYSTAL UNITS.**—The individual crystal or *unit cell* of crystal formation is of course exceedingly minute. The smallest of the crystals we can actually see is a "built-up" affair composed of a number of unit cells. Crystals of the same substance are invariably identical in form under identical conditions and so "grow" around the unit cell until single larger crystals result, sometimes several inches across. Large crystals usually break up when heated strongly, disintegrating into a large number of smaller ones by reason of the presence of relatively weak planes of cleavage, the planes on which the atoms or molecules lie, such as those marked A-A, B-B, C-C in Fig. 1. Crystalline building stones and concretes made with them are therefore dangerous in a conflagration for this reason.

**CRYSTALLINE FORMS.**—It has been shown that one type of crystal is arranged on a cubic lattice. There are a number of other arrangements, some of which are shown in addition to the cubic form in Fig. 9. Some substances may assume more than one form; carbon is an example, diamond being merely carbon arranged as a cubic, and graphite as a hexagonal lattice. In Experiment 11 we found that the needle crystals of sulphur split up into smaller crystals after a time; what took place was that the atoms re-arranged themselves into another type of lattice. There are instances, when the same lattice is assumed by more than one substance, of their atoms becoming mixed in the resulting crystals.

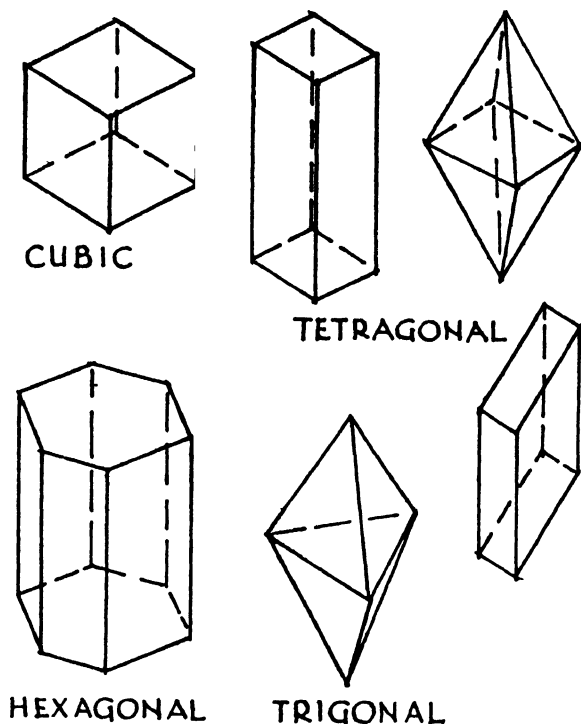


FIG. 9.—Common Forms of Crystal.

**CRYSTALLIZATION FROM SOLUTION.**—The characteristic features of crystals—plane, smooth, glittering surfaces meeting in straight lines at definite angles—are more usually apparent when solids crystallize from a solution rather than from a melt.

**EXPERIMENT 15.**—To prepare crystals from solution.

Prepare saturated solutions of sodium sulphate, sodium carbonate and copper sulphate (in their "dry" forms) in the following manner. Dissolve each in a beaker of water at ordinary temperature, stirring continuously until no more of the powder is taken up, then filter the solutions and put them aside in a cupboard for a week. At the end of this time remove the crystals, let them dry on a clean cloth or blotter and examine them, noting their forms.

**WATER OF CRYSTALLIZATION.**—With most crystalline substances, *e.g.* the metals, crystallization is the normal manner of solidification and the crystals contain nothing but molecules of the substance. Other substances do not crystallize except in the presence of water. To take as an example copper sulphate, each unit cell contains 1 molecule of copper sulphate *plus 5 molecules of water*. Without this water no crystals would form, and the copper sulphate would not be a crystalline substance.

The molecules of this *water of crystallization* are "loosely" attached to those of the copper sulphate (not chemically, for the substance is still copper sulphate), and can be driven away by increasing their heat motion, in other words by applying heat.

**EXPERIMENT 16.**—To show the effect of heat upon crystals.

Take some crystals of potassium chlorate in a test tube and hold in a bunsen flame. Crackling noises are soon heard and the crystals are seen to liquify and give off a gas. With a glowing wood splint test the gas by putting the glowing end into the tube. It immediately bursts into flame and burns brightly. It is therefore not steam but some other gas.

Next heat crystals of copper sulphate in the same manner. The effects are apparently similar, but on testing the gas given off it is found to extinguish the splint. Hold a flask of cold water to the mouth of the test tube and the gas will condense into drops of water on its sides. This is therefore steam.

We conclude from this experiment that the crystals of potassium chlorate do not contain water, but that water of crystallization is contained in the crystals of copper sulphate. If the liquid in the tube is boiled away we are left with a white powder, the dry or *anhydrous* form of copper sulphate.

**Amorphous Solids.**—In the case of a few substances cooling from the liquid state does not result in crystallization. They are usually materials which in their liquid state are of a highly viscous nature, and because of this the mobility of their molecules is reduced so much as to prevent their shuffling themselves into lattice formation on cooling to the solid state. They are called *vitreous* substances or *glasses*, and may be considered, in so far as their structure is concerned, as liquids of extremely (almost infinitely) high viscosity. Blast-furnace slag is an example.

The tendency to assume a vitreous state is increased by very rapid cooling and such supercooled liquids are in an unstable condition. Early types of window glass can frequently be seen to be cloudy and dull after the lapse of several centuries, due to its partial crystallization. The manufacture of glass nowadays is scientifically controlled and the possibility of failure of this kind is remote, but the thin glazes used on tiles and bricks, etc., do sometimes give trouble by reversion to the stable crystalline form and become opaque and liable to flake off.

Substances other than crystalline are called *amorphous*. The glasses belong to this group, as also do most organic substances.

A good example of an amorphous substance is the sulphur poured into water in Experiment 11. If this sulphur is taken from the water immediately it will be seen to be in a state resembling india rubber and can be stretched. It is sometimes called plastic sulphur, and its condition

is due to the instantaneous cooling having made crystallization impossible. If left for a week it will have reverted to a crystalline form like the needle crystals after the same length of time.

The ability of a solid to exist in several forms in this way is called *allotropy*.

**Conclusion.**—One of the most important facts to emerge from our study of the nature of matter is that, irrespective of the particular form it may take, gas, liquid or solid, whether its atoms are combined chemically with others of the same or different kinds, whether they are intermixed in solution, combined in colloidal particles or in crystals, they are always spaced apart and are not in actual contact. It may be difficult at first to think of a block of metal as being not perfectly "solid" but we must bear in mind the actual "size" of the atoms and their interatomic distances and not confuse them with tangible particles and pore spaces like the grains and pores of sandstone. We must also remember that the atoms are not lumps, however small, of solid matter but are themselves complicated systems. We shall then have no difficulty in comprehending all the phenomena of physical and chemical action and their application to building problems of all kinds.

## PHYSICAL MEASUREMENT

1. *Units of Measurement.*
2. *Measurement of Length.*
3. *Measurement of Area.*
4. *Measurement of Volume.*
5. *Mass, Force and Weight.*
6. *Density and Specific Gravity.*

## 1. UNITS OF MEASUREMENT.

In science it is necessary that all quantities should be capable of being expressed as exact measurements. To measure any quantity we must adopt a certain standard quantity of the same kind as that we wish to measure. This standard quantity is called the *unit* of measurement for the particular kind of quantity, and to express the measurement we must state the name of the unit and the number of times the quantity contains the unit.

The primary ideas with which we are concerned are those of *space*, *mass* and *time*, and the chief units are of these quantities.

The present British units are the *foot* (ft.), *pound* (lb.) and *second* (sec.).

The *foot* is the unit of length or linear dimension. It is actually one-third of the standard *yard* (yd.) which is the distance between two points on a certain bar of bronze, measured when the bar is at a temperature of 62 deg. Fahr. The *square foot* (sq. ft.) or *superficial foot* (ft. sup.) is the unit of surface area, and is the area of a square whose length of side is 1 ft. The *cubic foot* (c. ft.) is the unit of volume, and is the volume of a cube whose length of side is 1 ft.

The *pound* is the unit of mass, and is the mass of a standard piece of platinum, kept along with the other standards at the headquarters of the British Board of Trade.

The *second* is the unit of time, and is  $\frac{1}{86400}$  of the *average* day.

The Metric units are the *centimetre* (cm.), *gramme* (gm.) and *second* (sec.).

The *centimetre* is the unit of length, and is  $\frac{1}{100}$  of the standard *metre*, the length of a standard platinum bar at 0 deg. Cent. The *square centimetre* (sq. cm.) and the *cubic centimetre* (c. cm.) are the units of area and volume respectively.

The *gramme* or *gram* is the unit of mass and is  $\frac{1}{1000}$  of the mass of the standard *kilogramme* (kg.), a piece of platinum kept with other standards in Paris, France being the country of origin of the Metric system.



The *second*, the unit of time, is identical with the British second.

The mathematical tables of both systems will be known to the student, or will be studied in a course of Mathematics, and units for other quantities will be self-explanatory, thus :—" lb. per c. ft.", " metres per sec.", etc., etc.

The Metric system has many obvious advantages and is almost universally used in scientific work. In English-speaking countries, however, the British system is still in use for general purposes. We shall therefore find ourselves using both systems.

## 2. MEASUREMENT OF LENGTH.

The measurement of linear distances is one of the most important measuring operations, varying from the comparatively "coarse" measurement with yard stick or metre rule of distances of several feet, to "fine" measurements of anything down to a few hundred-thousandths of an inch made with "extensometers" and similar delicate instruments. It is proposed, however, to leave the consideration of the latter until the necessity for their use arises in dealing with strains, or minute movements of specimens under load in testing machines.

For present purposes we shall consider the use of the following :—

1. The boxwood rule and scale.
2. The steel rule.
3. The dividers.
4. The Vernier calliper.
5. The micrometer.

These are all in common use and enable us to measure accurately down to about  $\frac{1}{100}$ th of a millimetre or to about  $\frac{1}{3000}$ th of an inch.

**1. Boxwood Rules and Scales.**—Boxwood rules are of various kinds and include the following :—

- (a) The yard or 3-ft. rule. This is usually divided into inches, reading from 1 to 36, each inch being subdivided into eighths or tenths. Tenths will be found preferable to eighths as it is far more convenient to work in decimals rather than  $\frac{1}{8}$ ths,  $\frac{1}{16}$ ths,  $\frac{1}{32}$ nds, etc.
- (b) The metre rule is similar but divided into centimetres and millimetres. The metre rule may be bought with inches and subdivisions along one edge and centimetres and millimetres along the opposite edge.

These rules are from 1-in. to 1½-in. wide, and from  $\frac{3}{16}$ -in. to  $\frac{1}{4}$ -in. thick, with square edges. It is therefore necessary to avoid errors due to parallax. Fig. 10 shows how such errors may arise if the eye is

not truly perpendicular to the point B. The distance AB is  $1\frac{1}{4}$ -in. but if the eye is in position D instead of position C the reading is  $1\frac{1}{8}$ -in. To

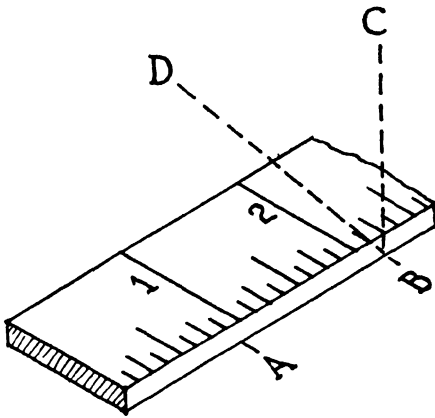


FIG. 10.  
Parallax Error in Reading from Rule.

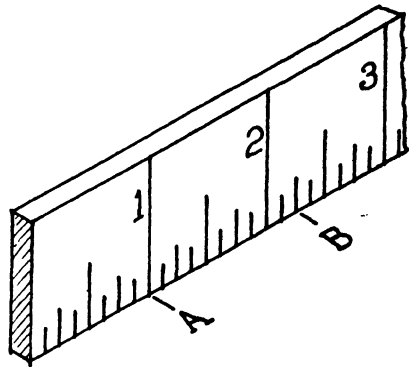


FIG. 11.  
Avoidance of Parallax Error.

make sure of obtaining an accurate reading it is always advisable to apply the rule on edge as in Fig. 11. It also makes for greater accuracy if readings are commenced not from the extremity of the rule, which may become worn even if brass-bound, but from a subsequent division mark such as from the 1-in. mark as shown. Care must be taken, however, to make the required deduction when stating the measurement. Rules of the folding type are neither so accurate nor so convenient.

- (c) For work in Graphic Statics the ordinary "architects'" scale is not nearly so convenient as one fully divided into inches and tenths and with one or two divisions in fiftieths. It should be of either of the two sections shown in Fig. 12 so as to give a greater degree of accuracy, and if expense is of little account it should be of ivory instead of boxwood. Any of the

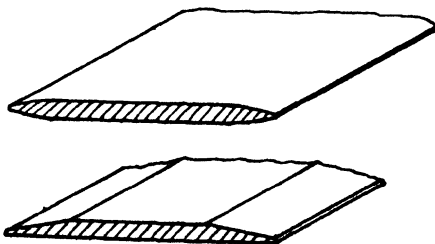


FIG. 12.—Scale and Rule Sections.

larger drawing instrument firms will supply an ivory scale just over a foot long with such a scale along one edge, the other edge or edges having the more usual scales. A single scale of this kind costing a guinea or thereabouts takes the place of several separate ones in boxwood at little extra cost, lasts for many years, and the price includes the engraving upon it of the name of the owner.

**2. The Steel Rule.**—The steel rule is just over a foot long,  $1\frac{1}{2}$ -in. wide and about 1 mm. thick, with square edges. The engineers' rule is divided into inches,  $\frac{1}{8}$ ths and  $\frac{1}{16}$ ths, with a few of the 1-in. divisions subdivided into  $\frac{1}{32}$ nds and  $\frac{1}{64}$ ths. The top edge has centimetres and millimetres, with a few  $\frac{1}{2}$ mm. subdivisions. For our work, however, the inches edge is better divided into  $\frac{1}{10}$ ths with a few  $\frac{1}{60}$ th subdivisions. This type is readily obtainable and is extremely useful for use in conjunction with dividers.

**3. The Dividers.**—The dividers should be the type used in engineering shops, as drawing dividers soon become worse for wear when used on metals, etc., instead of on paper. Fig. 13 shows a suitable kind, with adjusting screw which permits measurements accurate to  $\frac{1}{60}$ th-in.

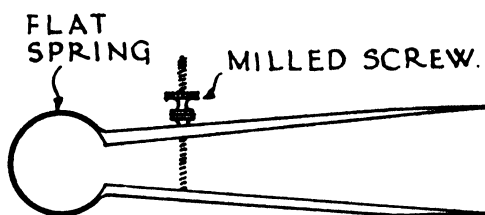


FIG. 13.—Steel Dividers.

**4. The Vernier Calliper.**—For measuring to  $\frac{1}{300}$ th-in. the vernier calliper is a very convenient instrument. It is made of rustless metal or plated steel and is illustrated in Fig. 14. It is obtainable with a scale

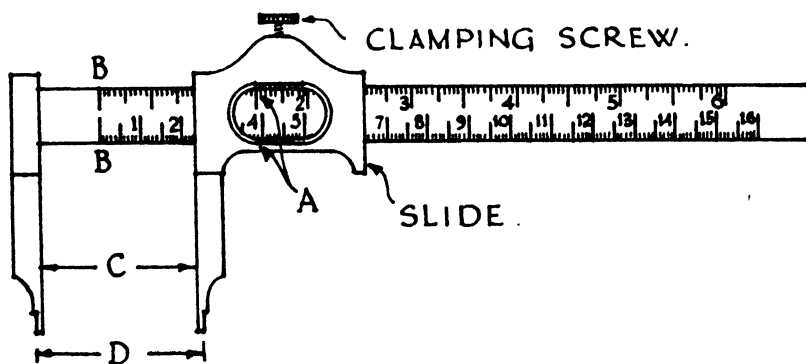


FIG. 14.—Vernier Calliper.

of centimetres and millimetres along one edge, inches and  $\frac{1}{10}$ ths along the other. The sliding jaw incorporates an open bevelled panel with the two verniers for giving readings of  $\frac{1}{10}$ th millimetre and  $\frac{1}{300}$ th-in. respectively. When the two jaws are in contact the zero A on each vernier is opposite the zero B on the corresponding scale. The scale reading at any other position of the sliding jaw therefore gives the distance C between the jaws. For measuring internal dimensions the jaws are used as in Fig. 15. In a metric calliper the dimension D is usually 2 mm. greater than dimension

C, and this amount must be allowed for. In a British calliper the difference is usually  $\frac{1}{100}$ th-in. If the calliper has both sets of scales such as the one we describe, then the difference between C and D should be measured and recorded on the instrument both in millimetres and in  $\frac{1}{100}$ ths-in. The reading shown in Fig. 14 is 3.81 cm. or 1.5-in.

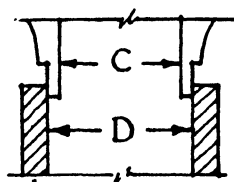


FIG. 15.  
Use of Vernier Calliper  
for Internal Measure-  
ment.

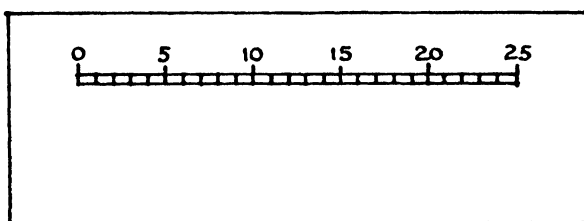


FIG. 16.—Principal Scale.

**VERNIER SCALES.**—Vernier scales are met with in so many types of measuring instrument that it is well briefly to explain their working. If a vernier scale should not be available to the student he should, for the purpose of mastering its use, construct one of paper in the following manner.

Take a sheet of drawing paper and draw on it a straight line, dividing it by ticking off from a scale into a number of equal parts, each say  $\frac{1}{10}$ -in. long. Number them from left to right, 0, 1, 2, 3, etc., up to about 30. This is the *principal scale* and is shown in Fig. 16. The vernier is set out on a narrow strip of similar paper, say 1-in. wide, which may be cut from the edge of the same sheet, and somewhat longer than the principal scale. On the upper edge of this strip set out a distance equal to 9 divisions of the principal scale and divide it into 10 equal parts, numbering them as before, 0, 1, 2, 3, etc. Cut two vertical slots just below the principal scale so that the vernier strip may slide horizontally along it as shown in Fig. 17. Now, as 10 vernier divisions equal 9 principal divisions, then each vernier division will equal  $\frac{9}{10}$  principal division.

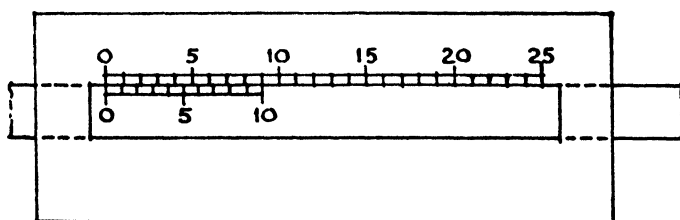


FIG. 17.—Principal and Vernier Scales.

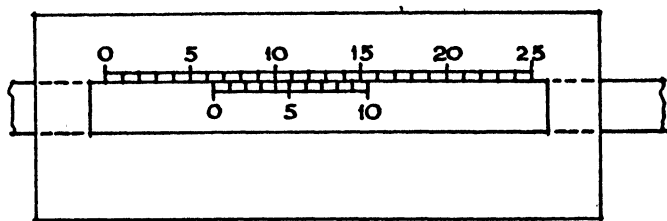


FIG. 18.—Use of Vernier Scale.

The reading shown in Fig. 18 is 6.4 units, and this is arrived at as follows:—The vernier zero is at 6+ on the principal scale, *i.e.* between 6 and 7. If it had been at 6 exactly, then the vernier 10 would have coincided with a principal scale division, the 15 to be exact. If it had been exactly half way between 6 and 7, that is at 6.5 the vernier 5 would have coincided with a principal scale division. What we have to do then, after having noted the position of vernier zero, is to look along the vernier from left to right and note which vernier division most nearly coincides with any principal scale division. The number of this vernier division, in Fig. 18 the 4, gives us the number of tenths to add to our whole number—if we are undecided between two adjacent vernier numbers, say 6 and 7, the fraction to add would be .65.

It will be seen that if our principal scale divisions are  $\frac{1}{10}$ th-ins. the vernier enables us to read accurately to  $\frac{1}{100}$ th-in., and by estimation to  $\frac{1}{200}$ th-in. More accurate vernier scales permit of measurement to  $\frac{1}{1000}$ th-in.

**5. The Micrometer.**—The micrometer, or to give it its full name, the micrometer screw gauge, consists of a screw the end of which moves forward a definite distance, either 1 millimetre or  $\frac{1}{40}$ th-in. for each complete revolution. The screw is threaded through one side of an anvil and moves

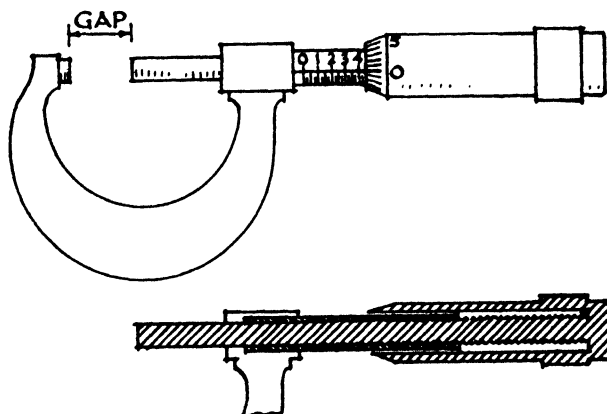


FIG. 19.—Micrometer Screw Gauge.

in relation to a fixed point on the other side, so enlarging or reducing the gap between them. The linear scale on the metric micrometer is divided into millimetres and the barrel is a divided circle of 100 equal parts. As a complete turn of the barrel moves the screw 1 millimetre then a partial turn of 1 barrel division moves the screw  $\frac{1}{100}$ th-millimetre. On the British micrometer the linear scale is in  $\frac{1}{10}$ ths and  $\frac{1}{40}$ ths, one complete turn moving the screw  $\frac{1}{40}$ th-in. or .025-in. The barrel is divided into 25 divisions each representing  $\frac{1}{1000}$ -in. or .001-in. In both cases estimation between the barrel divisions enables still finer measurement to be done, this depending upon the skill and judgment of the operator.

Normally micrometers are quite small, say a maximum gap of 2 cms. for Metric and 1-in. for British, but for special purposes they are available with much larger gaps; also special models are arranged for taking internal measurements.

**EXPERIMENTAL ERRORS.**—In all cases where measurement is done an experimental error is unavoidable due to the degree of accuracy of the instrument and the degree of skill of the user. To minimise this error all operations should be performed several times and the mean result taken. This applies to all quantitative experimental work and not merely to linear measurement.

#### Exercises in Linear Measurement.

1. Make two marks at random, about 2 ft. 6 in. to 3 ft. apart along the edge of the desk or table, and measure the distance with yard or metre stick. Then make 2 or 3 intermediate marks dividing the distance into 3 or 4 roughly equal parts (by estimation). Measure the distances with the steel rule, add, and compare the result with the first overall reading. Make a written record of the experiment as shown in Fig. 20.

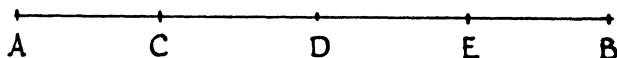


FIG. 20.—Example of Coarse Linear Measurement.

A written record such as this should be made of every operation and experiment—in a rough note book at the time, and later in a “fair” laboratory note book. This is preferable to entering up direct into the “fair” book, as some experiments are protracted and may even extend over a number of weeks, with other and unrelated work done in between. The student should look upon legible and intelligible recording as part of the experiment and so cultivate an orderly mind. Wherever a sketch is possible it should also be included but should be neatly done, otherwise the appearance of the record will be marred. Our first impression, and that of examiners and others, is always involuntarily gained by a quick glance through the book, and it is always sketches or other illustrations that catch the eye first.

2. Make two fine pencil marks on paper a few inches apart, measure the distance direct with the steel rule, and check with the spring dividers applied first to the two points and then to the scale. Record the experiment.
3. With the "tenth" boxwood scale set out along a straight line a distance representing 496 lb. to a scale of 100 lb. to the inch. Repeat with other quantities and scales.
4. Using the vernier calliper determine the diameters of various pencils, rods, etc., in Metric and British units, checking each with the appropriate micrometer. Do not "force" the instruments.
5. With vernier calliper or micrometer measure the thickness of a piece of glass, sheet lead or tinplate, etc. Clamp several pieces together, measure the overall thickness, calculate the mean thickness and compare with the first reading.

### 3. MEASUREMENT OF AREA.

The measurement of areas involves linear measurement in addition to subsequent calculations, and the methods of arriving at the areas of regular and irregular figures forms part of a course in mathematics. They will therefore not be discussed here, but an experimental method which is useful for complicated figures is given.

Trace the figure on to the surface of a flat sheet of stout paper or thin metal and cut around the outline. Then cut from the same material a square or other figure whose area is easily and accurately calculated and weigh both pieces.

$$\text{The Area of figure} = \text{Area of square, etc.} \times \frac{\text{Wt. of figure}}{\text{Wt. of square.}}$$

### 4. MEASUREMENT OF VOLUME.

At this point it may be well to distinguish between volume and *capacity*. Capacity applies only to hollow bodies and is the internal volume, in other words the volume of liquid, etc. held when full.

**Volume of Liquids.**—Separate units are in use for capacity to those normally used for volume, but they are not always used.

The British unit is the *gallon* and is equivalent to the volume of 10 lb. of water at 62 deg. Fahr., and as eight pints go to the gallon we get the useful memory-aiding rhyme: "A pint of water—a pound and a quarter." The relation between the British units of capacity and volume is therefore not simple, one gallon being the equivalent of 277.46 c. ins.

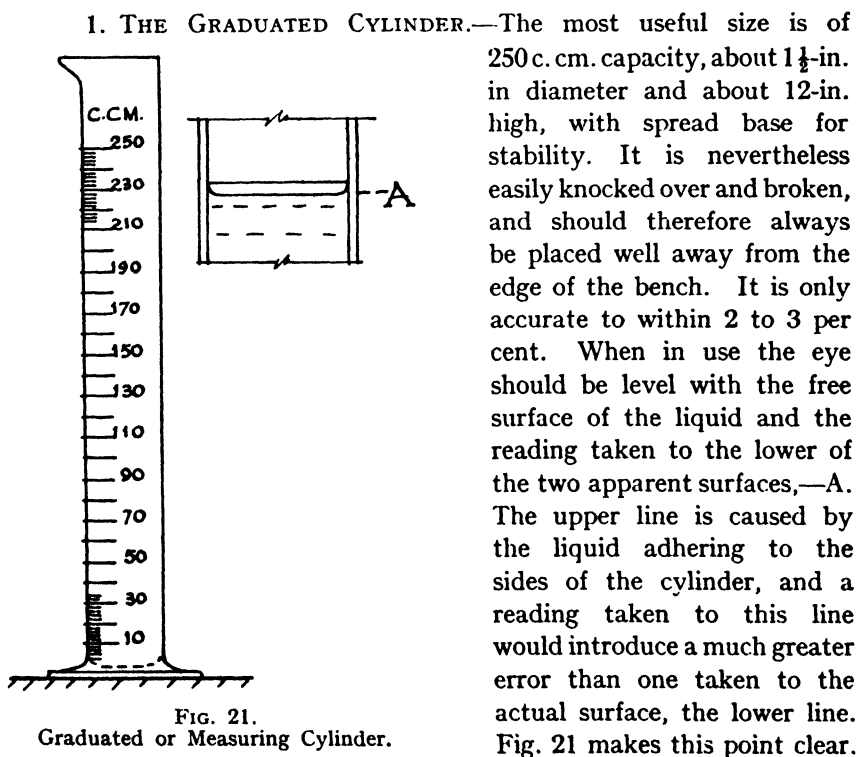
The Metric unit is the *litre* and this is definitely related to volume as well as to weight, being merely another name for the cubic decimetre. The weight of water (at 4 deg. Cent.) occupying 1 c. decimetre is 1 kilogramme or 1,000 gm. As there are 1,000 c. cm. to 1 c. dcm. and 1,000 milli-litres to 1 litre we find the two terms (c. cm. and m.l.) used for identical

purposes on measuring vessels. Further, as there are 1,000 gm. in 1 k.gm. we have the weight of 1 c. cm. or 1 m.l. of water (at 4 deg. Cent.) 1 gm. It is easy to see why there are so many advocates of the universal adoption of the Metric system.

The vessels in common use for measuring liquids are :—

- |                            |                   |
|----------------------------|-------------------|
| 1. The graduated cylinder. | } Both graduated. |
| 2. The burette.            |                   |
| 3. The pipette.            | } Not graduated.  |
| 4. The "graduated" flask.  |                   |
| 5. The S.G. flask.         |                   |

All are invariably made of glass, although for use in experimental work on concrete aggregates larger measuring vessels of metal, with the graduated scale on the inside, are invaluable.



2. THE BURETTE.—This is a long narrow glass tube, open at the top and constricted at the bottom, with a controlling tap near the bottom and below the termination of the scale. It is shown in Fig. 22. It is securely clamped to a stand during



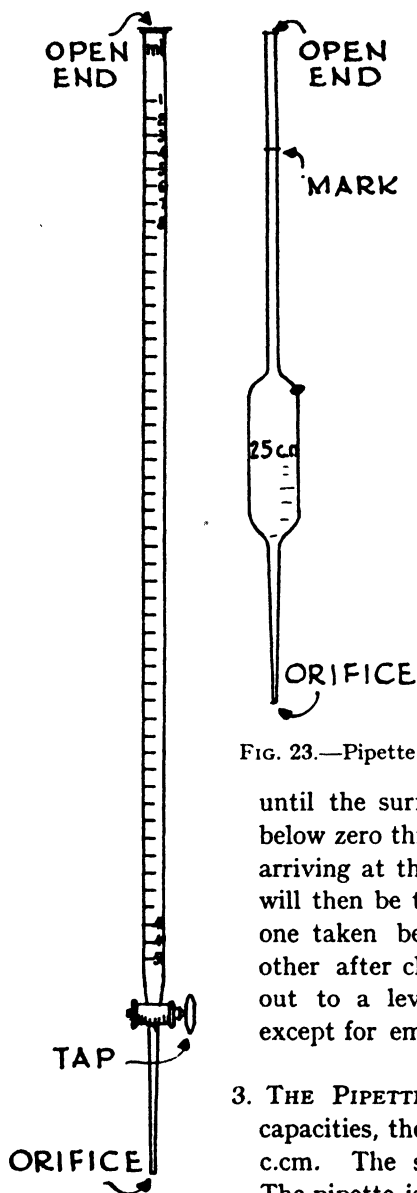


FIG. 23.—Pipette.

use, preferably an iron stand, but if only a wooden one is available its base should be "weighted" with a brick or a 7-lb. iron weight. A burette of 50 c.cm. capacity is about 30-in. long and  $\frac{1}{8}$ -in. diameter. As they vary slightly in diameter and as the bore may not be absolutely true, each is calibrated separately, and the best kinds are therefore rather expensive. This applies also to the more accurate graduated cylinders and other measuring vessels. The scale is invariably in c.cm. with 10 subdivisions to each, the smaller division thus being 0.1 c.cm. In use, liquid is poured into the burette from the top. Zero on the scale is uppermost and if the liquid reaches a higher level than this the surplus must be withdrawn by opening the tap

until the surface is at zero or below it. If it is below zero this fact must not be lost sight of when arriving at the volume of liquid withdrawn; this will then be the difference between two readings, one taken before turning on the tap and the other after closing it. Liquid must not be drawn out to a level below the bottom of the scale except for emptying.

3. THE PIPETTE.—Pipettes are made of various capacities, the most usual being 10, 25, 50, 100 c.cm. The smaller sizes are most easily used. The pipette is a glass tube blown out to a larger diameter near the centre, and drawn out at the lower end. On the neck, somewhere near the top, is a horizontal ring or mark, and when the pipette is full to this mark it contains the stated volume. To use the pipette the lower end is immersed in the liquid contained in a beaker or other vessel, the mouth is applied to the top and liquid drawn

up by suction until the mark is passed. The pipette is then withdrawn and the forefinger immediately placed over the top, so retaining the contents. To release liquid until the level coincides with the mark the pressure of the finger is eased slightly; this requires some practice as if it is quite removed only momentarily too much will probably be allowed to escape. To empty the pipette the finger is removed and the contents permitted to run out. A small blob of liquid will remain suspended from the orifice and this may be released by touching on the side of the receiving vessel; it should not be blown out, and needless to say no saliva should enter the pipette at any stage of the operation. The pipette and the burette are much more accurate, the error being only about  $\frac{1}{10}$  that of the graduated cylinder.

4. THE "GRADUATED" FLASK.—This is a flask with a rather long, thin neck and having a ring or mark upon it in the correct position according to its stated capacity. It may or may not be stoppered, and is not graduated in the sense that it has no scale. It is used merely to contain the stated volume of liquid for the purpose of weighing, etc. It is easily overturned as will be seen from Fig. 24.

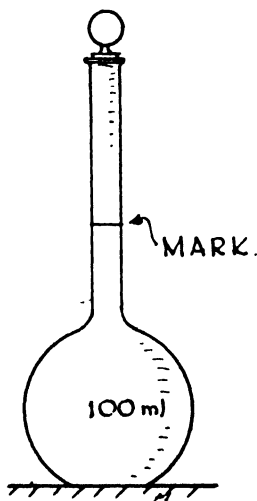


FIG. 24.—Graduated Flask.

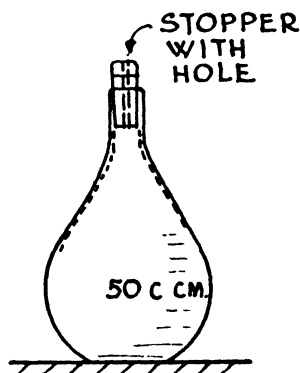


FIG. 25.—S.G. or Specific Gravity Flask.

5. THE S.G. FLASK.—The S.G. flask or bottle is rather similar and is used in experiments to find Specific Gravities. Its use will become apparent in a later section of this chapter. It is sturdily made and has an accurately fitting glass stopper

through which runs a fine hole. The flask is filled with liquid and the stopper gently inserted, when surplus liquid will be forced out through the hole. The flask is then full to the top of the hole and contains the stated volume. If the stopper is replaced too suddenly the surplus liquid will be squirted out forcibly; with practice, however, the flask may be filled to such a point that this surplus is negligible in amount. The flask is then dried before putting down. A very important point is that the stopper used should be the correct one for a particular flask, otherwise although possibly a perfect fit its base may not reach the exact point in the neck of the flask to give the correct capacity. The length of the stopper may also be incorrect, and consequently that of the hole which is of course included in the capacity. To avoid mistakes both the flask and its correct stopper have a distinguishing number scratched on, and before use it should be verified that the identical number appears on both.

All glass vessels should be perfectly clean and dry before use. Dilute hydrochloric acid may be used for cleaning out, and after washing out with water a little spirits shaken up, poured out, and the remainder allowed to evaporate is a convenient means of ensuring dryness. Drying will be accelerated when necessary by blowing in a current of dry air.

**Volume of Solids.**—This is a very common requirement, usually as a preliminary stage in the determination of other properties of bodies. The volumes of regular geometrical solids, as such, will not be discussed.

**METHOD 1.**—By direct measurement and calculation.

To find the volume of, say, a wirecut brick, measure with the steel rule the length, breadth and height of the brick, and from this data calculate its volume. Each of the three dimensions should be the mean of four taken near both edges of opposite faces, owing to the slight irregularities of the specimen. Enter up as follows:—

**EXPERIMENT 17.**—To determine the volume of a wirecut brick.

Length of brick (mean of 9.1, 9.2, 9.0, 9.1)	= 9.1 in.
Breadth „ „ (mean of 4.3, 4.3, 4.2, 4.3)	= 4.275 in.
Height „ „ (mean of 2.7, 2.75, 2.75, 2.8)	= 2.75 in.
Therefore Vol. = 9.1 in. × 4.275 in. × 2.75 in.	= 106.98 c.in.
	= <u>0.062 c.ft. approx.</u>

**METHOD 2.**—By displacement of liquid.

If the solid is irregular in shape, and therefore difficult to measure directly, its volume may be found by noting the volume

of water or other suitable liquid which it displaces when submerged. For bodies small enough to go into a measuring vessel, put into the vessel a known volume of liquid, lower into it the solid on the end of a fine thread, and take a reading of the liquid level, after making sure that no air bubbles are adhering. The difference between the two volumes is equivalent to the volume of the solid.

**EXPERIMENT 18.**—To determine the volume of an irregular specimen of metal.

Volume of water in graduated cylinder	= 67.2 c.cm.
Volume after solid immersed	= 94.4 c.cm.
Therefore Volume of solid = 94.4 — 67.2	= <u>27.2 c.cm.</u>

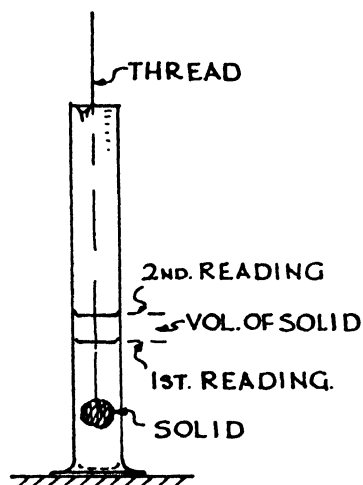


FIG. 26.—Volume of Small Solid by Displacement.

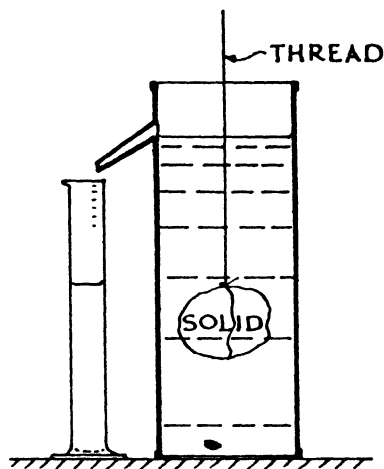


FIG. 27.—Use of Displacement Can.

For a larger solid a displacement can is used as shown in Fig. 27. These are obtainable in various sizes. The can is filled to a point higher than the overflow and the surplus water allowed to escape. The solid is then introduced gently and the displaced water collected and measured; this should be done several times and the average taken.

For use with bricks, large concrete specimens, etc., a galvanized steel open cistern of about 20 gal. capacity, fitted with an overflow pipe near the top is extremely useful as it can be used for many other purposes too.

**EXPERIMENT 19.**—To determine the volume of a blue pressed brick.

Pressed bricks have frogs of various forms and usually maker's initials or trade mark, etc. They are thus difficult to measure other than by displacement. Blue bricks are sufficiently impervious to water to dispense with preliminary soaking.

The specimen is immersed three times, the displaced water collected and measured each time being :—

1st immersion	..	..	..	2,162 c.cm.
2nd	„	..	..	2,158 c.cm.
3rd	„	..	..	2,166 c.cm.

Vol. of specimen = average displacement

$$= \frac{2,162 + 2,158 + 2,166}{3}$$

$$= 2,162 \text{ c.cm.} = \underline{0.076 \text{ c.ft.}} \quad (\text{See graph, page 49.})$$

If the solid is such as would be adversely affected by water a more suitable liquid would be used.

For a solid which floats, a thin rod or stout wire may be used to hold it *just below* water level whilst the second reading is being taken or the displaced water run out. Alternatively a heavy object may be used as a sinker, attached by thread to the solid and of suitable length. The first reading is then taken with the sinker and as much as possible of the thread submerged.

If the solid would absorb water, such as stone, etc., it is first thoroughly soaked and the surface wiped to remove surplus water before immersion.

Divided solids such as sand are measured by graduated cylinder in the same way as a liquid, if the "bulk" volume is required. In this case the sand must be well consolidated by tapping and the surface levelled. As a rule, however, it is the "grain" volume which is required. This is the volume of the solid particles alone, not including the inevitable air spaces between them. To obtain the grain volume the solid is poured gently into a known volume of liquid, stirred until all imprisoned air is released, and a second reading taken, the volume of the solid then being the difference between the readings. Or the solid may be introduced into the cylinder first, then the known volume of liquid added by pipette or other suitable means.

Paraffin and turpentine are suitable liquids to use in most cases where chemical action would result from the use of water, for instance cement, plaster and lime.

## 5. MASS, FORCE AND WEIGHT.

The amount of matter contained in a body is termed its *mass*. This obviously is quite independent of its volume since we can compress some bodies into a smaller volume without affecting their mass. Instances also come readily to mind of substances equal volumes of which have widely different masses; for instance a cubic ft. of lead obviously contains more matter than the same volume of cork.

There is no direct means of measuring the mass of a body, since mass equals quantity of matter and all substances are not composed of the

same kind of matter. But we have a convenient means of comparing masses as will be seen when we have learnt the meaning of the term *weight*.

**Force.**—A body in a state of rest has no inherent power to move or change its position. To do this it must be influenced by some agency external to itself, a *force*. The measure of the reluctance of the body to change its state of rest (or motion) when acted upon by a force is called its *inertia*.

Force may thus be defined as that which causes a body to move. For instance a footballer taking a penalty kick runs to the ball as it lies on the ground and gives it a kick, applying a force to it and causing it to move. But if the ball were made of lead or iron the same force would be unlikely to cause it to move. We must therefore amend our definition to something like this :—" Force is that which causes, or tends to cause, a body to move." This, however, is not sufficient, for the goalkeeper, in catching the ball, applies a force to it in order to bring it to rest. If, instead of stopping the ball, he had deflected it over the bar or punched it out he would still have applied the force, not in these instances to produce rest but to alter the course of the ball, in other words to alter its movement in a straight line. To complete our illustration, suppose the lead or iron ball to have been substituted for the real one and a particularly hardy player had been able to shoot it at the goal. This time the goalkeeper tries to stop it but is knocked over and the ball continues its flight, but at a reduced speed. He has still, however, applied a force to the ball. Our complete definition is therefore this :—*Force is that which changes, or tends to change, the state of a body, whether of rest or of uniform motion in a straight line.*

**Weight.**—All particles of matter exert a force of attraction upon each other, the attraction being proportional to the masses of the particles and inversely proportional to the square of their distance apart. Now bodies are aggregations of matter, therefore a large body always tends to attract a small one. Let us refer to Fig. 28 and imagine that the spheres are bodies acted upon by no forces other than this attraction. The bodies would be drawn towards each other until they meet as shown.

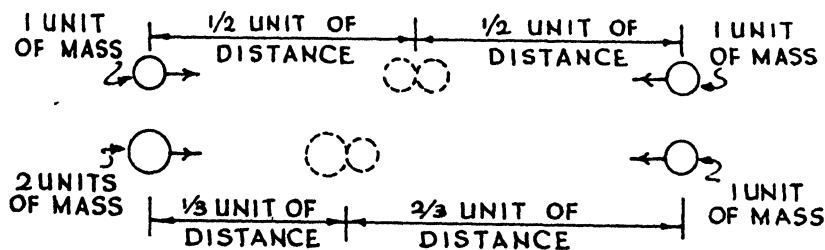


FIG. 28.—Mutual Attraction of Bodies.

It is fortunate, however, that this kind of thing cannot happen, otherwise all matter, ourselves included, would be packed together into a "solid mass." The reason is that all the bodies with which we are concerned are acted upon by the attraction of the earth, whose mass is so immeasurably great compared to theirs that their attraction for each other is inoperative. This force is called a gravitational force or *gravity*, and its effects are sufficiently well known to need little elaboration here.

The magnitude of the gravitational pull on a body is called its *weight*, and is proportional to the amount of matter contained in it, in other words to its mass. Here, then, is our means of measuring mass, although we must always remember that the two terms do not mean the same thing. Mass is an amount of *matter* and weight is a *force*, but when we need to know the mass of a body and find it by weighing the body we naturally refer to the result as the weight and not the mass. In *Building Science* we may be permitted to use the word "weight" in cases where we should strictly say "mass."

The weight of a body differs in different parts of the earth since the earth is not a perfect sphere, and the mass of earth between the body and the earth's centre varies, but this variation is negligible. If a body weighing, say, 1 lb. could be taken to a larger planet and weighed there (by spring balance) it would be found to weigh more than 1 lb. because the larger planet would exert a stronger gravitational force. The mass of the body would however remain the same.

**Measurement of mass or weight.**—In the Building laboratory a body is weighed either by balancing its mass against those of bodies of standard mass, called weights, or by noting the effect of its weight upon a steel spring.

The apparatus used in the first case comprises the scales and the balance, in the second case the spring balance. The scales and the balance will be described here, but consideration of the spring balance, used normally for measuring forces other than weights, will be deferred until we deal with forces generally in the second Section of this volume.

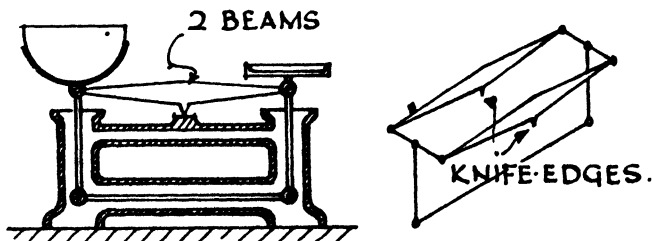


FIG. 29.—The Scales.

**THE SCALES.**—The scales are used for weighing comparatively heavy objects such as bricks. They should be of the kind made to weigh up to 14-lb. and capable of weighing accurately to about  $\frac{1}{8}$ -oz. They are shown in the sketch (Fig. 29). The weights usually supplied with such scales are :—7-lb. (iron), 4-lb., 2-lb., 1-lb., 8-oz., 4-oz., 2-oz., 1-oz.,  $\frac{1}{2}$ -oz., and  $\frac{1}{4}$ -oz. (all brass). A better arrangement for our work, one which saves endless time in converting ounces to decimals of a lb., is to discard the 2-oz. and smaller, substituting brass disc weights of the values :— $\cdot 1$ -lb.,  $\cdot 05$ -lb.,  $\cdot 02$ -lb.,  $\cdot 01$ -lb. By calling the 8-oz.  $\cdot 5$ -lb. and the 4-oz.  $\cdot 25$ -lb. we can now weigh from  $\cdot 01$ -lb. up to 7-lb. in increments of  $\cdot 01$ -lb.

The scales should be kept scrupulously clean and should be adjusted before use to ensure that the pans are exactly balanced. The object to be weighed should be placed *gently* into the correct pan and a weight estimated to be too large placed in the other pan (not necessarily the largest weight). If it should be too large remove it gently and substitute the *next smaller*, and so on through the range of weights until the pans exactly balance. Whenever the weight added proves too much replace it with the *next smaller*; whenever it does not prove too much proceed also with the *next smaller*. Much time will be saved by following this methodical procedure in every case.

**THE BALANCE.**—The physical balance is shown in Fig. 30. It varies in points of detail according to the degree of accuracy obtainable, but the type shown is suitable for our work and is sensitive to 1-milligram, although results correct to 5-mg. ( $\cdot 005$  gm.) are usually sufficiently accurate. It should not be used for weighing more than 250-gm. It

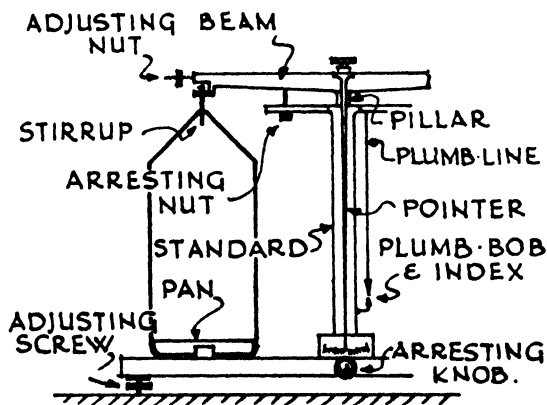


FIG. 30.—Physical Balance.

consists essentially of a beam supported by a central knife-edge of agate on the top of a vertical pillar. Near each end of the beam is another knife-edge supporting a stirrup from which the pan is suspended in a wire



frame. A pointer is fixed to the centre of the beam and swings with it so as to give readings on the scale. This latter is fixed low on the front of a hollow standard screwed down to the wood base, and inside which the pillar (together with beam and pans) can be raised or lowered by turning the arresting knob, clockwise or anti-clockwise respectively. When the knob is turned anti-clockwise the pillar is lowered by means of a cam on the knob spindle, the beam is lowered on to the two arresting nuts so relieving the central knife-edge of its weight, and the pans rest on the base board so taking their weight off the end knife-edges. The balance is kept in a glass-fronted case.

The weights should not be kept otherwise than in the special box shown in Fig. 31. They comprise brass weights :—

100-gm., 50-gm., 20-gm., 20-gm., 10-gm., 5-gm., 2-gm., 2-gm., 1-gm., and nickel weights :—

500-mgm.,	(.5-gm.)	Hexagonal.
200-mgm.,	(.2-gm.)	Square.
200-mgm.,	( " )	"
100-mgm.,	(.1-gm.)	Triangular.
50-mgm.,	(.05-gm.)	Hexagonal.
20-mgm.,	(.02-gm.)	Square.
20-mgm.,	( " )	"
10-mgm.,	(.01-gm.)	Triangular.
5-mgm.,	(.005-gm.)	Hexagonal.
2-mgm.,	(.002-gm.)	Square.
2-mgm.,	( " )	"
1-mgm.,	(.001-gm.)	Triangular.

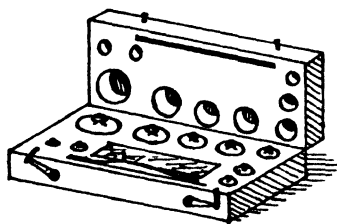


FIG. 31.—Standard Metric Weights for Physical Balance.

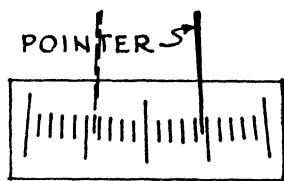


FIG. 32.—Estimation of Balance by Equal Displacement of Pointer.

A pair of tweezers is included for handling the weights and they should never be touched in any other way. It is invariably found that the 1-mgm. and 2-mgm. weights soon become unrecognisable or lost, but results to this degree of accuracy are seldom required in a Building laboratory.

To use the balance the procedure is as follows :—Raise the front of the case, but do not remove it or it will be broken, and slide the balance

firmly to the rear of the case so that it will not easily be moved during use. Place the case on the bench or table away from draughts or vibration, see that the beam and pans are lowered, and test the pillar for verticality by observing whether the plumb bob hangs vertically over its indicator. If not, turn one or both adjusting *screws* until it does. Then raise the pillar by turning the arresting knob, so lifting the beam off the arresting nuts. The beam will now be freely balanced on its knife-edge and the pointer will swing gently to and fro across the divided scale. The beam is truly horizontal (and the pans truly balanced) when the end of the pointer comes to rest in front of the central division of the scale, but instead of waiting for this to happen the amount of swing on both sides of the centre may be noted. The divisions on the scale represent no particular units, they are merely for this purpose, and when the pointer swings an equal amount on either side it will, on coming to rest, be in the centre. If this does not happen the beam should be lowered, one or both of the adjusting *nuts* (on the ends of the beam) turned slightly so as to adjust the equilibrium of the beam, the beam again raised, and the behaviour of the pointer noted afresh. This should be repeated until the beam is accurately balanced and the beam then lowered again.

We are now ready to commence weighing. Place the object to be weighed in the *left-hand* pan as near to the centre as possible, open the box of weights, remove the glass slip covering the smaller weights, and with the tweezers lift out the 100-gm. weight and place it on the *right-hand* pan. (Unless the operator is left-handed—when this should be reversed.) Raise the beam *slightly* and the initial movement of the pointer will indicate whether the weight is too much or too little. There is no need to raise the beam fully and observe the full swing of the pointer until near the end of the weighing operation. The procedure is then as outlined for the use of the scales, continuing with the other weights in descending order, *omitting none*, but the beam and pans *must be lowered every time a weight is added to or removed from the balance*. A little practice may be necessary before the balance can be used easily and quickly.

Here is a list of important “do nots” which should be memorized.

*Do not* lean upon or otherwise vibrate the bench or table whilst weighing.

*Do not* remove the glass front of the case.

*Do not* cough or breathe heavily into the case.

*Do not* forget to keep the pans lowered, except when observing the effect of adding a weight.

*Do not* handle the weights other than with the tweezers.

*Do not* place a wet or hot object in the pan.

*Do not* place loose substance such as cement directly in the pan.

Weigh first an empty vessel, then the vessel plus the cement, then deduct.

*Do not* view the pointer except from a position from 2 ft. to 3 ft. *directly* in front.

*Do not* replace the weights in the box until their values have been totalled and written down. The best plan is to jot down the individual values, starting with the largest and working in descending order, *before removing any from the pan*, checking them by noting which weights are missing from their appropriate compartments in the box.

Finally, *do* remember that a physical balance is a delicate and expensive instrument, and act accordingly.

#### Exercises on the Use of the Scales and Balance.

1. Using the scales find the weight of various types of brick.
2. Weigh, on the scales, a cement briquette mould.
3. Weigh 6 briquette moulds together, calculate the mean and compare with 2 above.
4. Weigh out, say, 2.26 lb. of portland cement. (This should be weighed in an appropriate vessel as follows :—  
 Balance the empty vessel with weights or otherwise, place weights to the full amount on the pan, and introduce the cement with scoop, trowel or spatula until the weights are just more than balanced. Then remove a little cement on the trowel, etc., and by tapping lightly allow it to trickle back until the pans balance.)
5. On the balance weigh a 1-oz. or 2-oz. weight. (1-oz. = 28.35-gm.)
6. Weigh six small pieces of chalk, first separately and then together. Compare the results.
7. Find the weight of a clean, empty beaker. Then add from a pipette 50 c.cm. of water and weigh again. Calculate the weight of 1 c.cm. of water.
8. Weigh a small piece of sheet lead, measure its area and thickness and calculate the weight per c.ft. of lead. (Approx. 710 lb. per c.ft.)
9. Weigh a plywood, bitumen dampcourse, sheet glass, etc., sample, measure the area and calculate the weight per sq. ft.

## 6. DENSITY AND SPECIFIC GRAVITY.

**Density.**—If we wish to compare different substances for “lightness” we have to compare the compactness of their particles together with the kind of matter of which they are composed. This is called their *density* and is what we mean when we sometimes refer to a substance as being “light” or “heavy.” Density relates to mass *and* volume, for the more matter that is contained in a given volume, say one unit of volume, the denser the substance. Now, as we measure mass by weight, we can

measure density by merely finding the weight of one unit of volume ; we may therefore put it :— $\text{Density} = \frac{\text{Weight}}{\text{Volume}}$ .

The densities of building materials are expressed in *lb. per c.ft.*, although we may have our direct experimental result in *gm. per c.cm.*, depending upon the type of specimen and the means adopted to measure its weight and volume.

**DENSITY OF GASES.**—This is naturally very small compared to liquids and solids, for instance Hydrogen normally weighs .00009 gm. per c.cm. and steam .0006 gm. per c.cm. The density of gases is not of great importance to us except in problems relating to the atmosphere.

**DENSITY OF LIQUIDS.**—To determine the densities of liquids we need only weigh a known volume, and for this purpose a graduated flask is most convenient. If one such flask is kept for this type of experiment its weight when empty can be scratched upon it and so save much time.

**EXPERIMENT 20.**—To determine the density of water.

Weight of flask when empty	= 20.66 gm.
Capacity of flask to mark	= 50 c.cm.
Weight of flask and water	= 70.52 gm.
Therefore Weight of 50 c.cm. of water = 70.52 — 20.66	= 49.86 gm.
Therefore Density = $\frac{49.86}{50}$	= <u>.997 gm. per c.cm.</u>

We have seen previously that the weight of 1 c.cm. of water should be exactly 1 gm. If the experiment were carried out without experimental error in a temperature of 4 deg. Cent. and using perfectly pure water this would be the result. For the degree of accuracy we require we may assume in all our experiments that the density of water is 1 gm. per c.cm., equivalent to 62.43 lb. per c.ft.

**DENSITY OF SOLIDS.**—We are concerned mainly with solids, and their densities are readily calculated from the data obtained by weighing and by measuring their volume as already described.

**EXPERIMENT 21.**—To determine the density of a wirecut brick.

Weight of brick (by scales)	= 8.27 lb.
Volume of brick (by direct measurement)	
= 9 × 4.2 × 3.05	= .0665 c.ft.
Therefore Density = $\frac{8.27}{.0665}$	= <u>124.3 lb. per c.ft.</u>

**EXPERIMENT 22.**—To determine the density of a sample of building stone.

The sample is too irregular to be measured with a rule and must therefore be measured by displacement.

Weight of stone dry = 34.44 gm.

Sample immersed in water for 1 hour, removed and surface dried.

Volume of displaced water (av. of 15.2, 15, 15.1) = 15.1 c.cm.

$$\begin{aligned} \text{Therefore Density} &= \frac{34.44 \text{ gm.}}{15.1 \text{ c.cm.}} &&= 2.29 \text{ gm. per c.cm.} \\ &&&= \underline{145 \text{ lb. per c.ft.}} \\ &&&(\text{See graph, page 49.}) \end{aligned}$$

**EXPERIMENT 23.**—To determine the density of a sample of building sand.

Weight of sand = 77.46 gm.

Volume of water in graduated cylinder = 100 c.cm.

Sand poured in and air released.

Second reading of graduated cylinder = 128.5 c.cm.

Volume of sand = 128.5 — 100 = 28.5 c.cm.

$$\begin{aligned} \text{Therefore Density} &= \frac{77.46}{28.5} &&= 2.72 \text{ gm. per c.cm.} \\ &&&= \underline{170 \text{ lb. per c.ft.}} \end{aligned}$$

**Specific Gravity.**—For purposes of comparison the density of one substance may be adopted as standard and all other densities related to it. If for instance we have two substances whose densities are 2 lb. per c.ft. and 10 lb. per c.ft. respectively and we take the first as our standard then the relative density of the second is 5, the ratio of its density to that of the standard.

The *relative density*, more usually termed the *specific gravity*, is therefore a ratio or number, not a weight or mass.

The standard substance used for comparing densities of gases is air, or sometimes hydrogen. For liquids and solids water is the standard (at 4 deg. Cent.) and since its density is 1 gm. per c.cm. the specific gravity of a substance whose density is, say, 10 gm. per c.cm. will be  $\frac{10}{1} = 10$ .

Using the Metric system the S.G. of a substance is therefore numerically identical to the density in gm. per c.cm., except that for the density the units must be specified.

With the British system the density of water (at 4 deg. Cent.) is 62.43 lb. per c.ft. and this is therefore the denominator in the S.G. fraction; the density and S.G. are thus not identical numerically.

The S.G. of any substance is therefore :—

$$\frac{\text{Weight of substance}}{\text{Weight of an equal volume of water.}}$$

**S.G. OF LIQUIDS.**—To find the S.G. of a liquid all we require is to weigh a known volume of the liquid and divide our result by as many gms. as there are c.cms. volume. For this purpose a graduated flask may be used but the S.G. flask is more convenient.

**EXPERIMENT 24.**—To determine the S.G. of paraffin. First method.

Weight of flask full of paraffin	= 63.20 gm.
"    "    " empty	= 20.67 gm.
Capacity of flask	= 50 c.cm.
Weight of 50 c.cm. of paraffin = 63.20 - 20.67	= 42.53 gm.
"    "    " of water	= 50 gm.
Therefore S.G. of paraffin = $\frac{42.53}{50}$	= <u>.85</u>

Other methods make use of the fact that water and other liquids exert an upward force (buoyancy) upon a solid immersed in them. The paragraph on the Principle of Archimedes on page 46 should be read before the next two experiments are carried out.

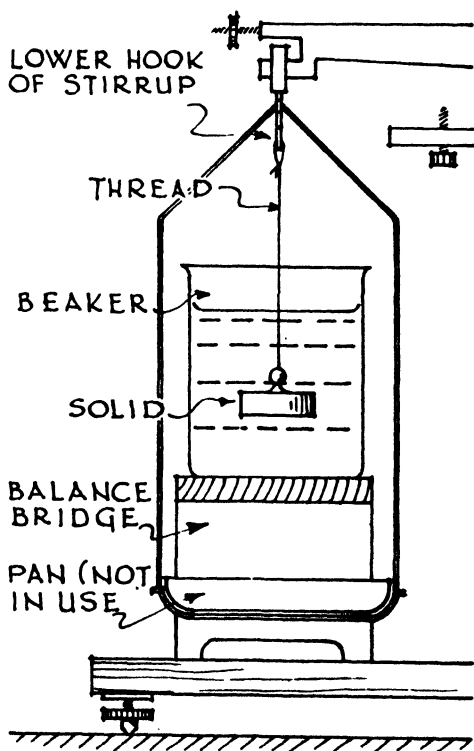


FIG. 33.—Weighing a Body suspended in Liquid.

**EXPERIMENT 25.**—To determine the S.G. of paraffin. Second method.

A suitable body, such as a small piece of metal (a spare 100 or 50 gm. weight is ideal) is attached to a thread and weighed on the balance. It is then weighed (a) whilst suspended fully immersed in water, and (b) whilst similarly suspended in paraffin. The method of doing this is shown in Fig. 33.

Weight of solid " in air " = 50.02 gm.

" " " " in water " = 44.16 gm.

" " " " in paraffin " = 45.03 gm.

Then, weight of water displaced by solid  
= 50.02 - 44.16 = 5.86 gm.

and weight of paraffin displaced  
= 50.02 - 45.03 = 4.99 gm.

But volume of water displaced  
= volume of paraffin displaced

Therefore S.G. of paraffin =  $\frac{4.99}{5.86} = .85$

**EXPERIMENT 26.**—To determine S.G. of paraffin. Third method.

A convenient solid is floated in water and the depth submerged measured. The body is dried and then floated in paraffin and the depth submerged noted. The body displaces a smaller volume of the denser liquid and therefore does not sink so deeply. A suitable solid is a test tube weighted with lead shot or a stick of wood about  $\frac{1}{4}$ -in. or  $\frac{3}{8}$ -in. square in section, greased or waxed to prevent absorption and weighted at the end to maintain it in an upright position when floating. (FIG. 34).

Depth submerged in water = 12.8 cm.

" " " paraffin = 15.0 cm.

Therefore S.G. of paraffin =  $\frac{12.8}{15.0} = .85$

This wood rod is a crude form of *hydrometer*. The usual hydrometer is a glass tube, closed at the top and blown out into two bulbs near the bottom. The lower bulb is filled with mercury to act as a stabilizer, the upper bulb is larger and contains air, so that the whole instrument floats upright. The stem has a scale engraved upon it giving readings of S.G. directly, without any calculation. In practice two general kinds are made, the scale being arranged so as to be suitable for liquids denser and less dense than water respectively. In addition it is made with special scales for particular trade purposes, *e.g.* for checking the S.G. of milk, beer, etc. The S.G. of the paraffin used in the preceding experiments should be verified by hydrometer. Other methods of finding specific gravities are given later.

**S.G. OF SOLIDS.**—The S.G. of a solid may be found from its density where this is known. For instance a solid whose density is 2.2 gm. per c.cm. has a S.G. of 2.2. In British units its density would be 137.35 lb. per c.ft. giving  $\frac{137.35}{62.43} = 2.2$  as the S.G.

As a rule, however, methods of arriving at the S.G. direct, without first determining the density, are simpler. The density can then be found from the S.G. if required by multiplying by 62.43 lb. per c.ft.

A pure substance has a definite S.G. which is always the same, and a test for S.G. discloses any adulteration, although not necessarily its nature.

A graduated flask or S.G. flask may be used in finding the S.G. of divided solids, both methods involving the displacement of a volume of liquid equal to that of the sample. The graduated flask will be used in the next experiment and the S.G. flask in the succeeding one. The capacity and weight of the flask are known, or may be found, also the weight of water held when full. The sample is put into the flask and the combined weight found. From a pipette water is then run in, sufficient to cover the sample, and all air bubbles released by tapping or agitating. The filling is then completed up to the mark and the whole then weighed. We then have all the data necessary for calculating the S.G.

EXPERIMENT 27.—To determine the S.G. of a sample of building sand. (Grains.)

Weight of graduated flask	=	47.51 gm.
"    "    flask + sand	=	109.85 gm.
"    "    "    "    + water	=	186.85 gm.
Capacity of flask	=	100 c.cm.
Weight of water to mark	=	100 gm.
"    "    sand = 109.85 - 47.51	=	62.34 gm.
"    "    water when sand is in	=	186.85 - 109.85
	=	77 gm.
Therefore Weight of water replaced by sand	=	100 - 77
	=	23 gm.
Therefore S.G. of sand	=	$\frac{\text{Weight of sand}}{\text{Wt. of equal vol. water}}$
	=	$\frac{62.34 \text{ gm.}}{23 \text{ gm.}}$
	=	<u>2.71</u>

EXPERIMENT 28.—To determine the S.G. of Portland cement.

At one time the British Standard Specification tests for Portland cement included the test for specific gravity, and although not now demanded it can profitably be carried out as the method is identical for limes, plasters and similar materials.

We shall use a S.G. flask for this experiment and introduce the liquid (paraffin or turpentine) from a burette, so measuring its volume directly.

Weight of S.G. flask	=	20.67 gm.
"    "    flask + cement	=	38.77 gm.
"    "    cement = 38.77 - 20.67	=	18.1 gm.
First burette reading	=	0 c.cm.
Second "    "	=	44.2 c.cm.
Volume of paraffin used	=	44.2 c.cm.



Capacity of flask	= 50 c.cm.
Therefore Volume of cement = 50 - 44.2	= 5.8 c.cm.
Weight of equal volume of water	= 5.8 gm
Therefore S.G. of cement = $\frac{18.1}{5.8}$	= <u>3.12</u>

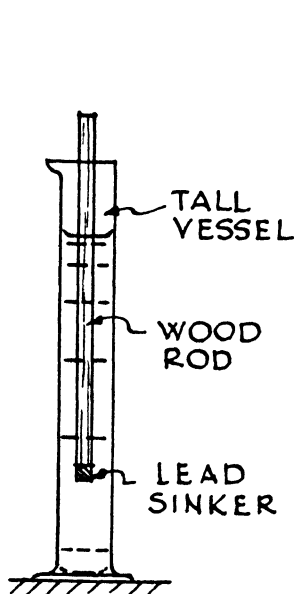


FIG. 34.—Floating Solid used to find S.G. of Liquid.

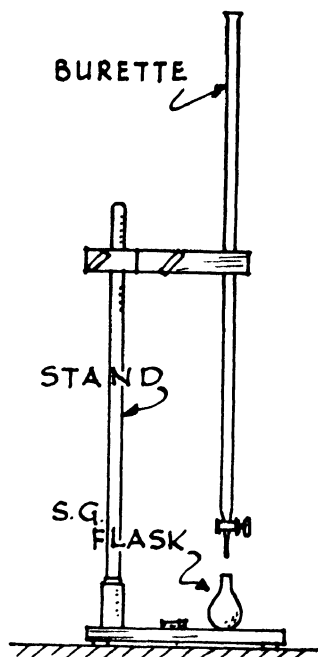


FIG. 35.—S.G. of Solid by S.G. Flask.

In Experiments 25 and 26, page 44, the buoyancy of liquids was utilized in order to find their specific gravity. This principle, the *Principle of Archimedes*, is also of importance to us in other respects.

A body of liquid normally preserves a level upper surface, and when we displace some of it, say by immersing a solid, we do not leave a depression on removing it. Instead the surface resumes its horizontality because the surrounding liquid, under the action of gravity, and because of the mobility of the liquid particles, sinks and in doing so pushes the liquid in the depression up to the general surface. If the solid should be a block of material having a density identical with that of the liquid it will be upheld by the upward force and will float just submerged, that is with its upper surface just level with the upper surface of the liquid. In other words it replaces a block of liquid of its own shape and volume. The weight of the displaced liquid and the weight of the solid are equal, since the one acting upwards balances the other acting downwards.

It follows from this that any solid immersed in liquid is subjected to an upward force *equal to the weight of the liquid displaced*.

If this upward force is greater than the weight of the solid the solid will float, and as it then does not displace its own volume of liquid its density is therefore less than that of the liquid. If the upward force is less than the weight of the solid the solid will sink, and as it has displaced its own volume of liquid its density is therefore greater than that of the liquid.

If in the latter case we weigh the solid first in the ordinary way and then whilst suspended in liquid it appears to have lost weight, this apparent loss of weight being equal to the weight of liquid displaced.

EXPERIMENT 29.—To verify the Principle of Archimedes.

Suspend a blue brick by a length of string to a spring balance and note its weight "in air." Then submerge the brick in a tank of water and note the new balance reading. Subtract to find the apparent loss of weight, and compare with the weight of a volume of water equal to that of the brick.

Weight of brick in air	= 9.7 lb.
" " " in water	= 5.3 lb.
Volume of brick (by measurement or displacement)	= .071 c.ft.
Weight of .071 c.ft. of water	
= .071 × 62.43	= 4.43 lb.
Apparent loss of weight of brick	
= 9.7 - 5.3	= 4.4 lb.

From these results we also have the data for finding the density and specific gravity of the brick.

$$\begin{aligned} \text{Its density} &= \frac{\text{Weight}}{\text{Volume}} = \frac{9.7}{.071} = \underline{\underline{136.6 \text{ lb. per c.ft.}}} \\ \text{Its S.G.} &= \frac{\text{Weight}}{\text{Wt. of eq. vol. water}} = \frac{9.7}{4.43} = \underline{\underline{2.19}} \end{aligned}$$

We have seen from Experiment 25 that the apparent loss of weight of a solid in water and in other liquid is sufficient data to give us directly the S.G. of the other liquid. In Experiment 26 we obtained the S.G. of a liquid by comparing the volume of water displaced with the volume of other liquid displaced, the weight displaced being the same in both cases.

Let us now make use of a floating solid to find its S.G. directly.

EXPERIMENT 30.—To determine the S.G. of a solid by flotation.

A suitable solid is a block of wood of easy dimensions such as shown in Fig. 36. It must be cut so that the grain is standing or lying, otherwise the block will not float level, and it should be greased or varnished to prevent absorption of water.

Float the block in water and make a mark on its side corresponding to the water level. Then remove it and measure the depth of the portion that was submerged. Now the weight of the displaced water is equal to the weight of the block.

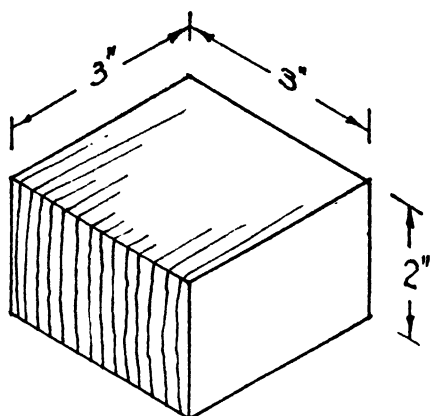


FIG. 36.—S.G. of Regular Solid by Flotation.

Therefore the S.G. of the wood

$$\begin{aligned}
 &= \frac{\text{Weight of submerged part}}{\text{Weight of displaced water}} \\
 &= \frac{\text{Weight of submerged part}}{\text{Weight of whole block}} \\
 &= \frac{\text{Volume of submerged part}}{\text{Volume of whole block}} \\
 &= \frac{(\text{Area} \times \text{depth}) \text{ of submerged part}}{(\text{Area} \times \text{depth}) \text{ of whole block}} \\
 &= \frac{\text{Depth of submerged part}}{\text{Depth of whole block}}
 \end{aligned}$$

If the depth submerged is found to be 1.25-in. then the S.G. is

$$\frac{1.25 \text{ in.}}{2 \text{ in.}} = \underline{\underline{.62}}$$

### Exercises on Density and Specific Gravity.

- Find the density of a concrete cube, etc. :—
  - By direct measurement and weight.
  - By weight and subsequent displacement.
  - By the Principle of Archimedes.
- Find the S.G. of a block of wood :—
  - By direct measurement and weight.
  - By flotation.
- Find the S.G. of turpentine :—
  - By S.G. flask.
  - By flotation of a solid.
  - By "loss of weight" of a solid.

TABLE 1.

<i>Material</i>	<i>Density (lb. c.ft.)</i>	<i>S.G.</i>	<i>Material</i>	<i>Density (lb. c.ft.)</i>	<i>S.G.</i>
Water .. ..	62.43	1	Limestone ..	av. 140	2.24
Turpentine ..	—	.87	Sandstone ..	av. 150	2.4
Paraffin .. ..	—	.8 to .85	Lead .. ..	707	11.3
Mercury .. ..	—	13.6	Cast Iron ..	450	7.2
Alcohol .. ..	—	.79	Mild steel ..	490	7.8
Blue brick ..	av. 137	2.19	Zinc .. ..	450	7.2
P.C. Concrete ..	av. 140	2.24	Copper .. ..	550	8.9
Dry sand (bulk)	av. 95	—	Aluminium ..	169	2.7
„ „ (grain)	170	2.72	Deal .. ..	av. 36	.57
Cement (bulk) ..	90	—	Oak .. ..	av. 54	.86
„ „ (grain) ..	193.5	3.1	Teak .. ..	av. 48	.76
Granite .. ..	av. 160	2.56	Ice .. ..	57.43	.93
Slate .. ..	av. 170	2.72	Glass .. ..	av. 160	2.56

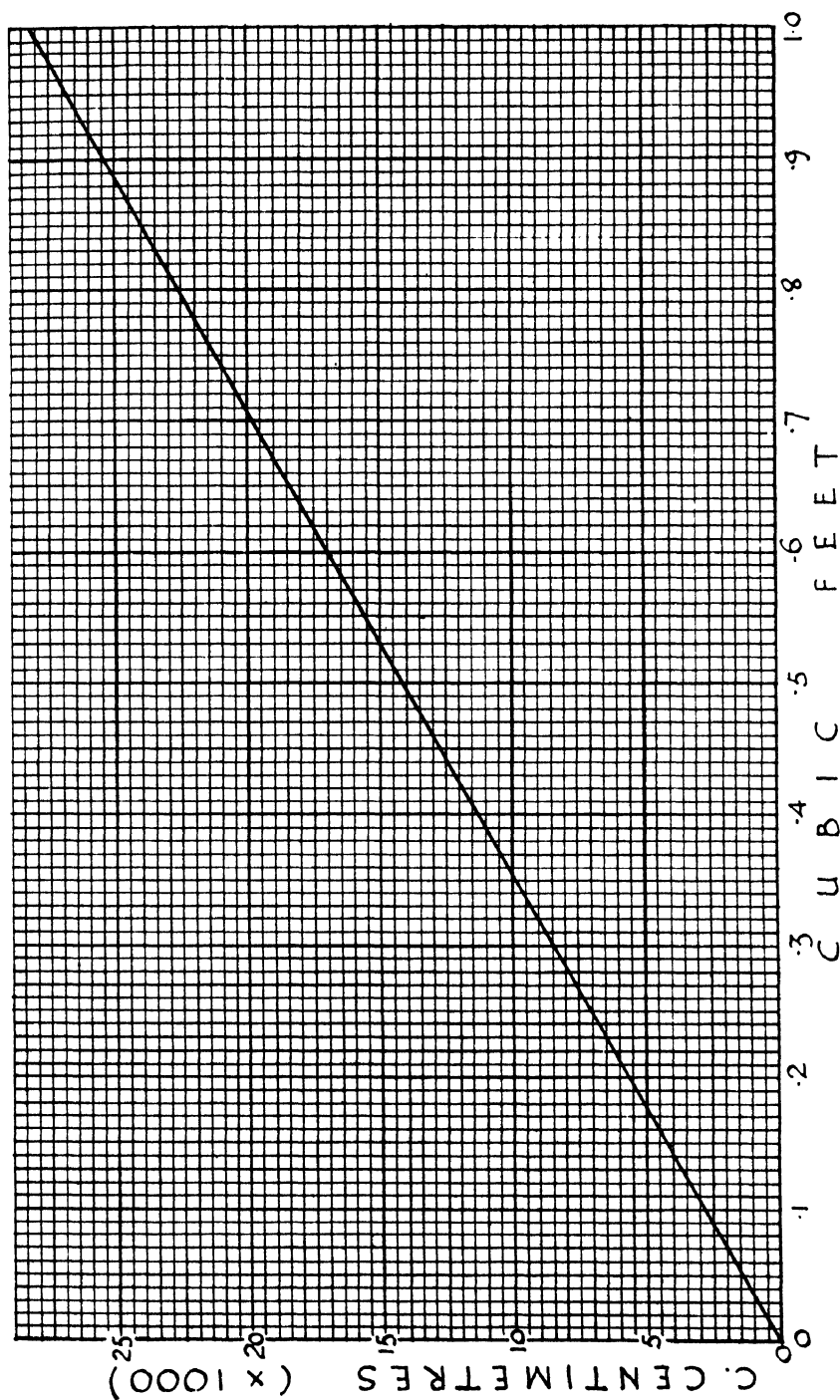


FIG. 37.—Conversion Graph. Cubic Centimetres to Cubic Feet.

## CHAPTER III

### SURFACE TENSION AND CAPILLARITY

1. *Surface Tension.*
2. *Capillarity or Capillary Attraction.*
3. *Effects of Capillarity in Practice.*

#### 1. SURFACE TENSION.

In a body of liquid a molecule below the free surface is surrounded by other molecules all exerting equal attraction upon it *from all directions*. The result is that the molecule is in equilibrium in relation to the others unless some other force is brought into play. But a molecule at the surface is attracted only by those beneath it and around the sides—it is therefore pulled equally from these directions *but not from above*, or only by the much more widely spaced molecules of air. The upper surface of the liquid is therefore subject to a constant pull sideways and inwards as shown in Fig. 38. The molecules at the surface cannot maintain their

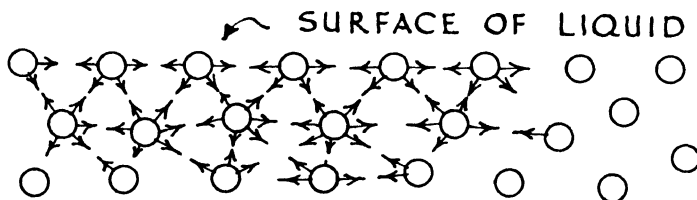


FIG. 38.—Illustrating Surface Tension.

equilibrium by moving inwards or sideways; if they are forced inwards or sideways by some other force others take their place. The free surface therefore acts as though it were covered by a thin elastic membrane. This is indeed the case, but the skin or membrane is formed of molecules of the liquid itself. This property is known as *surface tension*.

Surface tension can be demonstrated quite simply in many ways, and the following experiments are easily carried out.

#### EXPERIMENTS TO ILLUSTRATE THE SURFACE TENSION OF WATER.

##### EXPERIMENT 31.

Take a clean, undamaged gas jar, fill it to within about  $\frac{1}{4}$ -in. of the top with water and stand it on a level surface so that the ground rim is truly horizontal. Then fill a pipette with water and release it into the jar until the jar is just full, *i.e.* until the water is just level with the rim of the jar. Now continue to release water drop by drop and the surface will be found to rise appreciably *above* the rim of the jar, the surface having the actual appearance of being contained by a thin skin.

This experiment is a variation of the old party trick of filling a tumbler and inviting guesses as to how many pennies could then be dropped in without the water overflowing. The result was invariably startling to the uninitiated.

**EXPERIMENT 32.**

Take a dish or large beaker of water and with the point of a sewing needle gently poke or prod the surface. This will be seen to depress the water visibly without its surface being pierced.

Then hold the needle horizontally between finger and thumb just above the surface and drop it on to the water. If it was held truly horizontal the needle will float, notwithstanding the fact that steel is very much denser than water. A thin needle is best, such as the type used for threading small beads.

Surface tension, as might be expected, always tends to cause the surface of a liquid to contract. If, therefore, a body of liquid is not affected by any other force it assumes a spherical form, the sphere being the solid having the smallest surface area for a given volume. Water issuing slowly from a tap falls through the air in drops which are in the form of spheres. But for the force of gravity, which breaks the water up into tiny drops, the spheres would be much larger. A drop of water on a greasy surface, or a drop of mercury on the level surface of a table, etc., receives an upward reaction to counteract its own weight and therefore forms a flattened sphere.

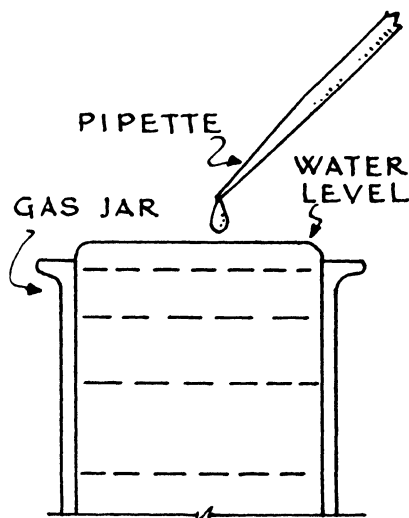


FIG. 39.—Demonstration of Surface Tension.

Surface tension does not act only at the boundary of a liquid and a gas. We can show that it acts at the boundary between two non-miscible liquids, and at the same time by eliminating the effect of gravity produce a perfect sphere of liquid of any size we wish. This is demonstrated in a striking manner in the following experiment.

**EXPERIMENT 33.**—To form a large drop of oil.

Secure a bell jar firmly in a stand, or stand any large glass vessel directly upon the table. Take a sufficient quantity of olive oil, according to the size of drop aspired to, and measure its specific gravity, by means of a S.G. flask or hydrometer. Then about one-third fill the jar with water and add alcohol, stirring and testing the S.G. from time to time with a hydrometer until

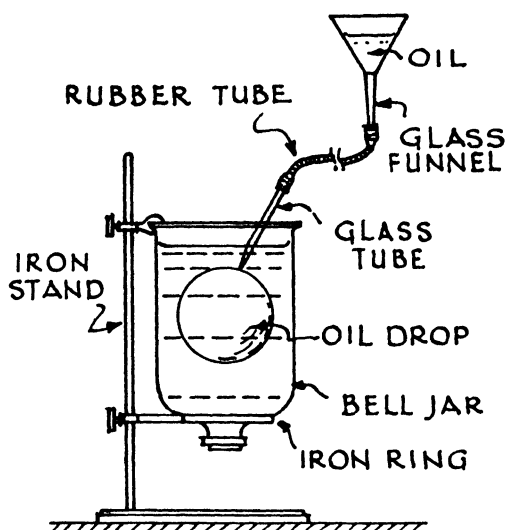


FIG. 40.—Formation of Spherical "Drop."

it is the same as that of the oil. Then by the means shown in Fig. 40 or in any other convenient way, introduce the oil slowly and continuously through a narrow tube.

It will be seen to form a spherical drop growing ever larger until the supply of oil is exhausted or until the bell jar is full. Now withdraw the pipette or tube and the sphere of oil will remain suspended motionless in the solution, not being acted upon by any force other than its own surface tension.

A soap bubble is a mass of gas enclosed by a film which by its contraction squeezes the gas into spherical form. The surface

tension of a soap film can be demonstrated in an interesting manner because of its minute thickness.

**EXPERIMENT 34.**—To show the surface tension of a soap film.

With two hairs or silk threads suspend a needle or short length of wire from a wire suitably arranged for holding in the hand, as shown in Fig. 41. Immerse in a soap solution and withdraw. The soap film will be seen to pull the two hairs inwards, on account of their lack of rigidity, and raise the needle.

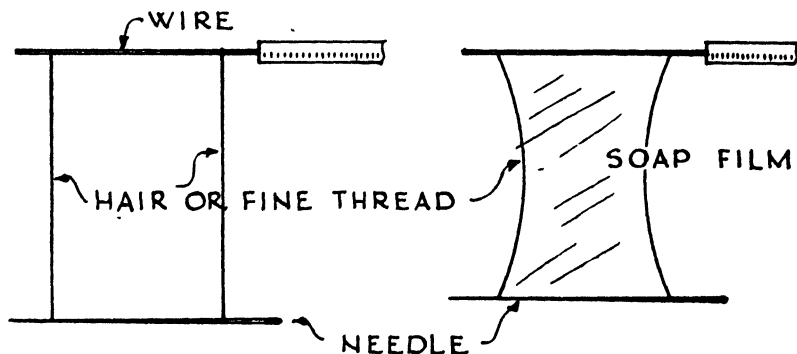


FIG. 41.—Surface Tension of Soap Film—1st Experiment.

In Fig. 42 a thin wire loop or frame is dipped into soap solution and withdrawn with a soap film stretched across it. A small loop of fine thread, wet with solution, is then laid upon the film and the film punctured inside the loop. This is best done with a hot

needle. The loop is immediately pulled out into circular shape, the circle being the figure having the shortest perimeter for a given area.

If we destroy the surface tension of water it does not split up into drops. This may be shown with a piece of apparatus called a "water hammer," which is a glass tube containing water, the air above the water being exhausted. In the vacuum so formed the water behaves almost as though it were solid, and upon the tube being inverted, the column of water falls to the other end making a hard, sharp sound upon impact.

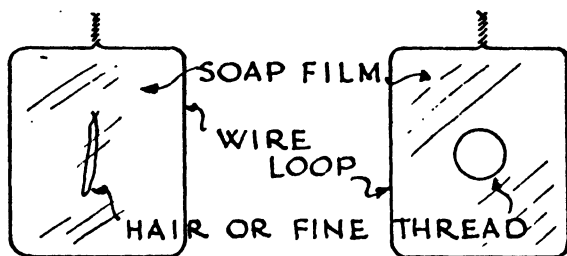


FIG. 42.—Surface Tension of Soap Film—2nd Experiment. \_

## 2. CAPILLARITY.

Surface tension is also known to be present at the boundary of a liquid and a solid, as between the liquid and the inside surfaces of a vessel. The most important case, however, so far as we are concerned is when gaseous, liquid and solid surfaces are all together in contact. This occurs on the upper surface of the liquid around the edge where the liquid meets the sides of the vessel.

In most cases, including water and aqueous solutions, the tension at the boundary of the solid and the gas is stronger than that between the liquid and the gas. (The tension between the liquid and the solid below the upper surface is of no importance in this connection.) We therefore have a kind of tug-of-war going on at the surface of the liquid, and Fig. 43 shows the result. The solid/gas boundary (A) is subject to a surface tension which tends to pull the liquid along the surface of the solid, vertically in this case. At the same time the liquid/gas boundary (B) is trying to shrink to a minimum area horizontally. But the vertical pull is the greater, and elsewhere as at C it does not operate. At C therefore, the liquid surface is horizontal under the action of gravity but at D the vertical pull wins, both against the horizontal pull and against gravity. The upper surface of the liquid thus assumes an upward curved form where it meets the solid, this curve being called a *meniscus*. We met an example of this phenomenon in reading from a graduated cylinder or burette in Chapter II.



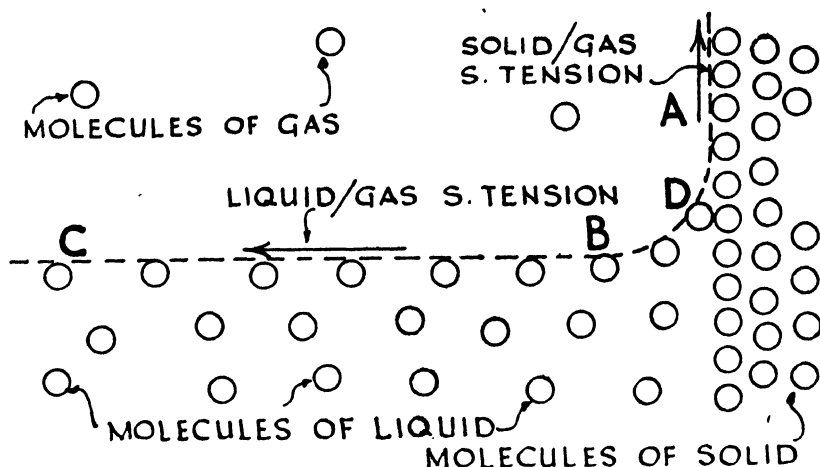


FIG. 43.—Capillary Meniscus in Liquid.

This adhesion of liquid to a solid surface we call "wetting" the solid. Mercury and other molten metals do not wet a solid surface, except certain metals, and water does not wet a greasy surface; the meniscus is therefore downwards in these cases. This is because the surface tensions between liquid and the air and between liquid and solid are greater than

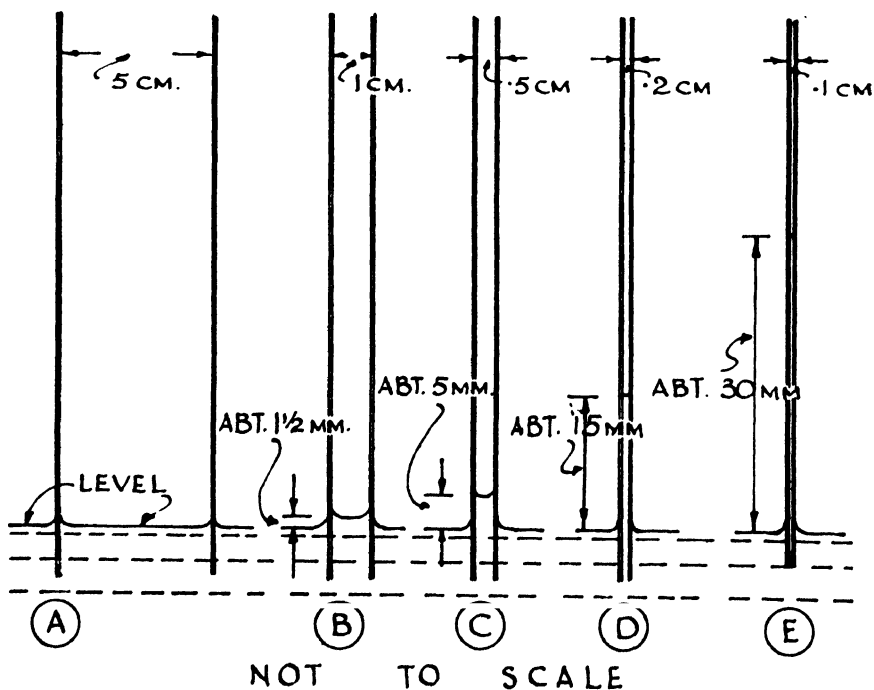


FIG. 44.—Effects of Capillary Attraction.

that between air and the solid ; in other words, referring to Fig. 43, the horizontal pull wins instead of the vertical one.

If we stand two clean glass plates vertically on edge in a shallow tray of water, and say 5 cm. apart, we get a meniscus on the inner surface of each plate. (Those on the outer surfaces do not concern us here.) If we close the gap between the plates to 1 cm. we find that they join to form a single curve and the level of its lowest point has risen slightly above the general water level in the tray. (Fig. 44B.)

What has happened is that the area of water between the plates is so small that the total water/air tension (the horizontal pull) has become so slight as to offer less resistance to the solid/air tension (the vertical pull). If we close the gap still further (Fig. 44, C, D, E) we find the vertical pull gradually gaining in superiority until the water between the plates stands at a level many inches higher than in the tray. This phenomenon is known as *capillarity*, because it was first observed in capillary tubes or glass tubes of fine bore. We could indeed use glass tubes of various diameter bore instead of the glass plates.

EXPERIMENT 35.—To show the effect of capillarity.

Take two clean glass plates such as lantern slide cover plates, a match and a rubber band. Place the match between the plates near one edge and clamp together with the rubber band as in Fig. 45 B. Then stand them vertically in a shallow tray containing about  $\frac{1}{4}$ -in. of water, and the effect seen at A will be observed.

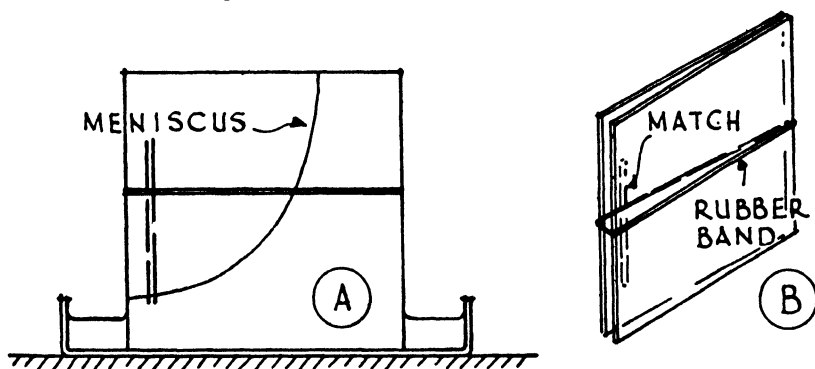


FIG. 45.—Meniscus caused by varying Width of Capillary Path.

### 3. EFFECTS OF CAPILLARITY IN PRACTICE.

Examples in building construction will doubtless occur to the student in which flat surfaces lie close together, and in all such cases where water has access it will travel between them in this way, not necessarily vertically, unless means are employed to prevent it. The only practicable method of doing this is to widen the gap between the surfaces at a convenient point. In Fig. 46 water flowing down the roof finds its way upwards between the

slates by capillarity assisted sometimes by wind pressure. If the slates were laid flat it would easily travel to the heads of the slates and so gain access to the timber construction beneath, with bad results. To prevent it the gap is widened by the use of tilting fillets at eaves and ridge, or at the eaves by a raised fascia board. The slight camber in the length of a roofing tile is made mainly for this purpose.

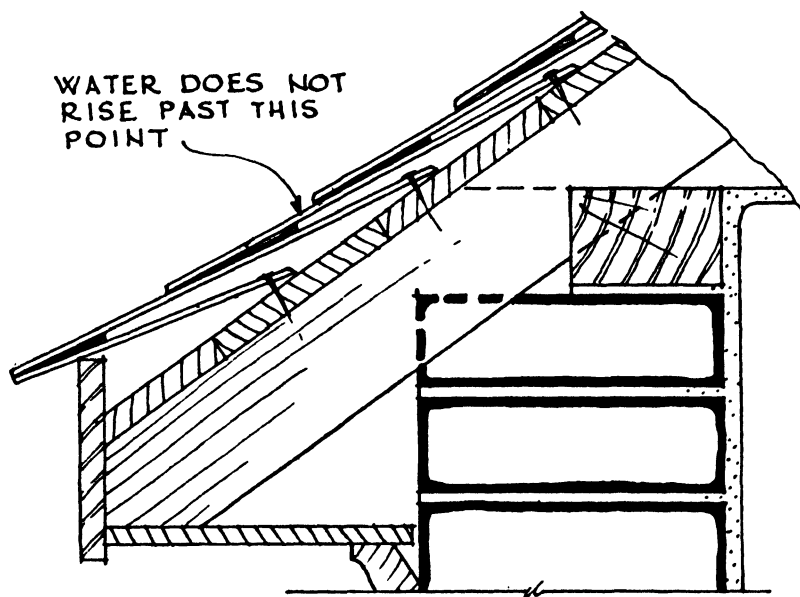


FIG. 46.—Capillarity between Slates on Roof.

Where a wood door or window meets its frame a fine space is left, and rain reaching the outer surface is drawn in by capillarity, quite apart from gravity or wind. Such a space is therefore usually widened by one or more "weather-grooves" as shown in Fig. 47. (These should not be confused with condensation grooves, which are merely to receive condensed moisture from the inner surface of the glass.)

In cases where sheet lead flashings are arranged to lie on top of a roof as in Fig. 48, or at the foot of a stack or dormer, there is great danger of water finding its way through unless a capillary groove is formed. This does not appear to be normal practice, but the writer has always found that the cost of dressing the lead over a wood stick or steel rod (subsequently withdrawn) is negligible and ensures immunity.

A case where the importance of grooving to resist capillarity is universally realised is in the construction of drips in sheet leadwork to a "flat" roof, illustrated in Fig. 49.

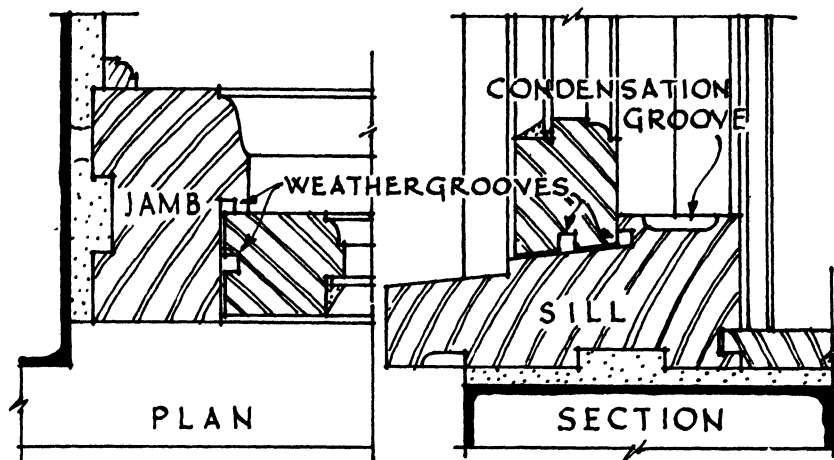


FIG. 47.—Anti-Capillarity or "Weather" Grooves in Joinery.

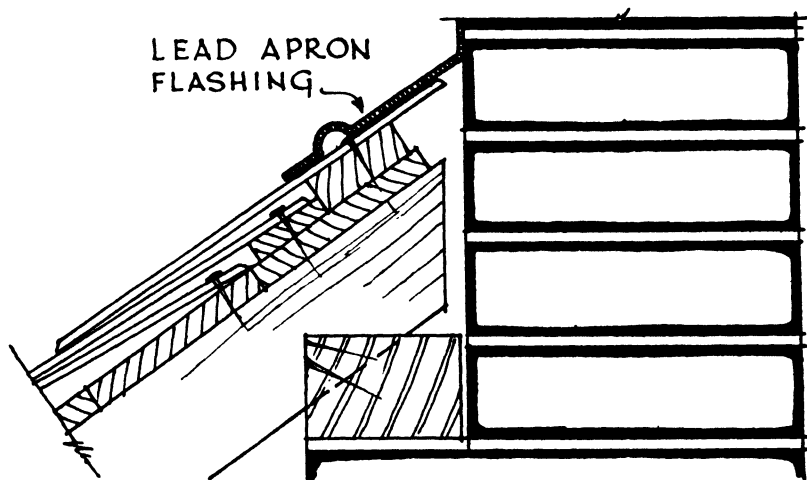


FIG. 48.—Anti-Capillarity Groove in Lead Flashing.

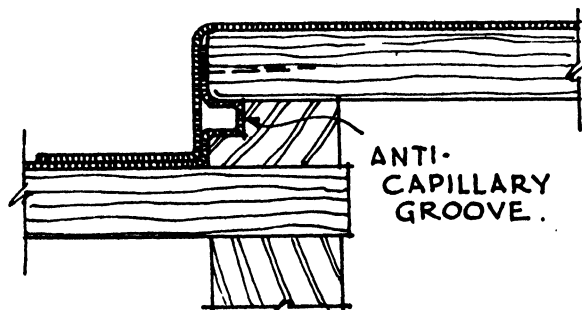


FIG. 49.—Anti-Capillarity Groove in Lead Drip.

A fine space such as these examples into which water can enter by capillarity is called a *capillary path*. Capillary paths abound everywhere, not only in building construction. The gardener hoes his soil in dry weather so that the moisture beneath is induced to rise ; but for capillarity the sap would not rise in plants and trees ; the oil in a lamp or candle rises up the wick by capillarity to be vaporized and burnt—the flat sauceboat shape of the oil lamps in Classic times was due to the low surface tension of olive oil, the illuminant used ; it was therefore unable to rise very far up a wick. Wicks used in conjunction with oil reservoirs are employed in machinery for ensuring very small but constant supplies to working parts. In one proprietary type of septic tank filter the effluent is discharged from the troughs on to the filtering medium by means of numerous wires which act as wicks.

The pores of any porous material such as bricks act as capillary paths if they are interconnected, as is usually the case ; this is of great significance and will be dealt with fully in Chapter IV. It may be mentioned here, however, that more important than the pores of bricks or stones and mortar joints are the capillary paths between them. If we were to try to prevent the entry of rain into a wall by using non-porous bricks and equally non-porous mortar we should still be unable to prevent it, for the shrinkage of the mortar on setting invariably results in loss of adhesion to the bricks, and leaves minute capillary paths between them and the mortar.

## THE POROSITY OF BUILDING MATERIALS

1. *Voids in Materials.*
2. *Relation of Porosity to other Physical Properties :—*
  - (a) *Density.*
  - (b) *Strength.*
  - (c) *Absorption.*
  - (d) *Surface Texture.*
  - (e) *Condensation.*
  - (f) *Insulation.*
3. *Impervious Materials.*
4. *Moisture Movement of Materials.*

### 1. VOIDS IN MATERIALS.

We concluded our study of the Structure of Matter (Chapter I) with the idea that no material is perfectly solid since its atoms or molecules not only contain space in themselves but are not in physical contact with each other. The atoms or molecules of all substances may be compacted more closely if a sufficiently strong force is applied, and this may lead to the idea that all matter is in some degree porous. Whether this is correct or not depends upon what we mean by the term "porous." In our study of *Building Science* we shall use the term "pores" to mean air spaces in the mass of a solid, in other words the voids between the grains or tangible particles of the solid. The interatomic space in a solid cannot contain air or any other substance.

Building materials may be classified as :—

(a) non-porous, and (b) porous.

Non-porous materials are those which have been formed by cooling from a molten state, viz. :—metals, "plastics," glasses, bitumen, marbles, granites and whinstone. We deal with these in detail in Section 3 of this Chapter.

Porous materials owe their structure to their different methods of formation, and include the majority of building materials. Timber is built up of strings of cells the sap from which dries out leaving air pockets. The cell walls are composed of fibre formed by the drying up of colloidal solutions, and these therefore also contain air spaces. Sandstones and some limestones were deposited as grains of eroded matter, sometimes

mixed with the calcareous products of minute animal life, in and around the mouths of rivers—they thus have voids, originally filled with water. The true limestones consist wholly of the remains of marine life; the magnesian limestones were solutes precipitated from solution in water owing to reduction in temperature and pressure. All these are therefore porous. Bricks and tiles are moulded from dry or plastic clay from which the moisture is driven off by firing—so leaving voids. The materials of concrete, mortar and plaster are mixed with water, most of which subsequently dries out—again leaving voids. Wood products, wall-boards and so on all obviously contain voids also.

## 2. RELATION OF POROSITY TO OTHER PHYSICAL PROPERTIES.

If we ask the average person what he understands by “porosity” or a “porous material” he will undoubtedly answer that it refers to a material having soaked up a lot of water—or words to that effect. Now, although a porous material is liable to “soak up” water, the word means simply that the material contains pores, in other words it is not solid in the way that a metal is solid.

**Porosity Related to Density.**—Under “Density and Specific Gravity,” in Chapter II, we referred to density as meaning the amount of matter contained in a given volume of substance. If our substance contains voids, then its density is lower than if it did not, because voids are not solid matter and yet they occupy some of the volume. In our study of densities of solids we distinguished between bulk volume and grain volume in the case of divided materials like sand. For solids like brick, etc., the density we determined was the *bulk density* and this included the voids. If we wish to know exactly how much of the bulk volume is taken up by voids we must (a) measure the volume of the voids, or (b) measure the volume of solid matter and deduct this from the bulk volume. There is no really satisfactory method of measuring directly the volume of the voids, but we discuss this question under “Absorption.” We can, however, readily obtain the volume of solid matter if we eliminate the voids by pulverizing the material. This can be done with mortar and pestle, taking care to grind it as finely as possible, so that none of the resulting grains itself contains voids. All that is then necessary is to determine the volume of the grains by displacement (page 34), and deduct this from the bulk volume of the piece before grinding. For comparison, the result is best expressed as a percentage.

**POROSITY PERCENTAGE.**—Following the method outlined in the last paragraph let us take an example.

**EXPERIMENT 36.**—To determine the porosity percentage of a red brick.

For easy powdering select a type of brick known to be fairly soft. Take a piece about  $1\frac{1}{2}$ -in. across and measure its volume. Then dry it thoroughly in a water oven and powder it, subsequently finding the grain volume.

Bulk volume of specimen (by displacement) = 5.46 c.cm.

Volume of grains (by displacement) = 4.02 c.cm.

Therefore Volume of voids = 5.46 — 4.02 = 1.44 c.cm.

$$\text{And porosity percentage} = \frac{1.44 \times 100}{5.46} = \underline{\underline{26.4}}$$

TABLE 2.

POROSITY PERCENTAGE OF TYPICAL MATERIALS.		
Material		Percentage
Red rubber brick	.. ..	35
Fletton, red pressed	.. ..	25—30
Staffs. blue brick	.. ..	8
Sandstone	.. ..	9—18
Limestone	.. ..	20—30
P.C. Concrete, 1 : 2 : 4	.. ..	10—12

The density of a building material naturally affects its weight and this is of importance as regards its function and position in the building. Building materials used mainly for their weight-carrying capacity must be dense, those which are to govern stability such as in retaining walls, buttresses, pinnacles, etc., must also be dense so as to secure as great a weight as possible with the minimum of material, for resistance to the percolation of water density is again required as in tanks, dams, etc.

In cases where the material is to be supported by other construction and not *vice versa* lightness is an advantage, provided that other essential properties are not sacrificed as in roofing and vaulting, concrete used merely for filling, partitions which are to be supported on floors, panels of non-weight-carrying walling, etc.

**Porosity related to Strength.**—By strength we mean in this connection strength in compression, or ability to withstand crushing force. Porous materials like brick are obviously unsuited to withstand stretching or tension, and timber is in a class to itself, although it is porous, on account of its fibrous structure. As the voids in a block of material are simply pockets of air they have no strength to resist crushing, and so we might expect strength to increase with a decrease of porosity. This we find to be the case as will be seen from the following brief table.



TABLE 3.

POROSITY AND CRUSHING STRENGTH OF TYPICAL MATERIALS.

<i>Material</i>	<i>Porosity percentage (Approx.)</i>	<i>Strength (Approx.) (Tons sq. in.)</i>
Red rubber brick .. ..	35	·25
Fletton, pressed .. ..	25—30	1·5—2
Staffs. blue brick .. ..	8	6—7
Sandstone .. ..	9—18	3—7
Limestone .. ..	20—30	1·5—3
P.C. Concrete, 1 : 2 : 4 .. ..	10—12	Up to 4 (after 1 year)

The metals have no voids and might therefore be expected to have very high crushing strength. Cast iron withstands 45 tons per sq. in. but lead, equally non-porous, can withstand practically no crushing. The truth is that in the case of material other than brick, concrete and stone, porosity is not the only criterion. In these materials (brick, etc.) we have a group whose grain density is for practical purposes identical, and so their porosity governs their crushing strength.

**Porosity related to Absorption.**—Absorption is the term used to denote the property of permitting liquid, usually water, to enter the voids of a material, and is perhaps the most obvious of the effects of porosity. It is well known that porous materials admit water, whilst non-porous ones do not. We have only to compare a brick with a glass block after immersion in water to discover that the brick, after removal, has increased in weight whilst the glass has not.

We intimated under " Porosity related to Density " that we cannot with certainty measure the volume of voids by the volume of water absorbed by a material. The reason is that the voids may not be entirely inter-connected ; some may be inside the mass of the material with no access from the surface, and the problem then depends upon the ability to admit water of the solid material bounding the voids. A very porous material may thus absorb less water than one of much lower porosity ; the important thing from the practical viewpoint is therefore not so much the exact degree of porosity as the behaviour of the material under actual conditions of use—and this depends largely upon its absorption.

Most building specifications contain a clause to the effect that bricks should not absorb more than  $\frac{1}{4}$  of their dry weight after 24 hours' immersion in water. As the amount of total absorption is not nearly so important as the rate at which initial absorption takes place it would be better to specify a maximum after a much shorter immersion, because weathering and certain types of disintegration take place at or near the surface, when the interior of the material may possibly be reasonably dry.

If we wish to obtain the total absorption of a material it is weighed room dry (after having been stored inside for some weeks and not merely brought from outside in damp weather) and then immersed in water for as long as convenient. Some materials may take several weeks to absorb their maximum quantity, others may be saturated in a few hours. To hasten the process the water may be boiling, and kept boiling throughout the test.

**RATE OF ABSORPTION.**—To compare the behaviour of different types of brick, stone, etc., it is more instructive to find the *rate* of absorption. The specimens should be of approximately identical size and are first weighed dry, then again after repeated short immersions until no further increase in weight is shown. After each immersion the specimen should be dabbed with a dry cloth to remove surface water before weighing—they should be of quite short duration at first, say 2 minutes for the first 5 or 6, then 10 minutes for the next 5 or 6, gradually increasing as the test goes on, until after an hour or so an interval of 30 minutes or an hour is sufficient. Below is a record of such a test on four different bricks shown both in table and in graph form. The graph is seen to be more convenient as the final form of the record, curves for all four bricks being shown on the same graph, but during the experiment it is better to jot down results as a table. The 14-lb. scales are used in conjunction with decimal weights as described in Chapter II.

**EXPERIMENT 37.**—To compare the rate of absorption of bricks.

		<i>Red rubber</i> Volume 200 c.in.	<i>Fletton</i> Volume 99.5 c.in.	<i>Pressed Eng.</i> Volume 81.8 c.in.	<i>Staffs. Blue</i> Volume 121.5 c.in.
Dry weight	..	11.98 lb.	5.32 lb.	9.04 lb.	9.39 lb.
After 2 mins.	..	13.05	5.81	9.08	9.4
„ 4 „	..	13.23	5.96	9.12	9.4
„ 6 „	..	13.35	6.05	9.15	9.4
„ 8 „	..	13.38	6.12	9.18	9.4
„ 10 „	..	13.43	6.17	9.21	9.41
„ 20 „	..	13.46	6.28	9.33	9.42
„ 30 „	..	13.5	6.32	9.39	9.42
„ 40 „	..	13.53	6.34	9.42	9.43
„ 50 „	..	13.55	6.35	9.44	9.43
„ 1 hr.	..	13.56	6.36	9.45	9.43
„ 1½ hrs.	..	13.57	6.37	9.45	9.44
„ 2 „	..	13.58	6.37	9.46	9.45
„ 2½ „	..	13.58	6.37	9.46	9.46
„ 3 „	..	13.59	6.38	9.46	9.47
„ 24 „	..	13.6	6.39	9.47	9.5
„ 2 days	..	13.6	6.4	9.47	9.57
„ 7 „	..	13.6	6.41	9.48	9.75
„ 14 „	..	13.6	6.41	9.49	9.85

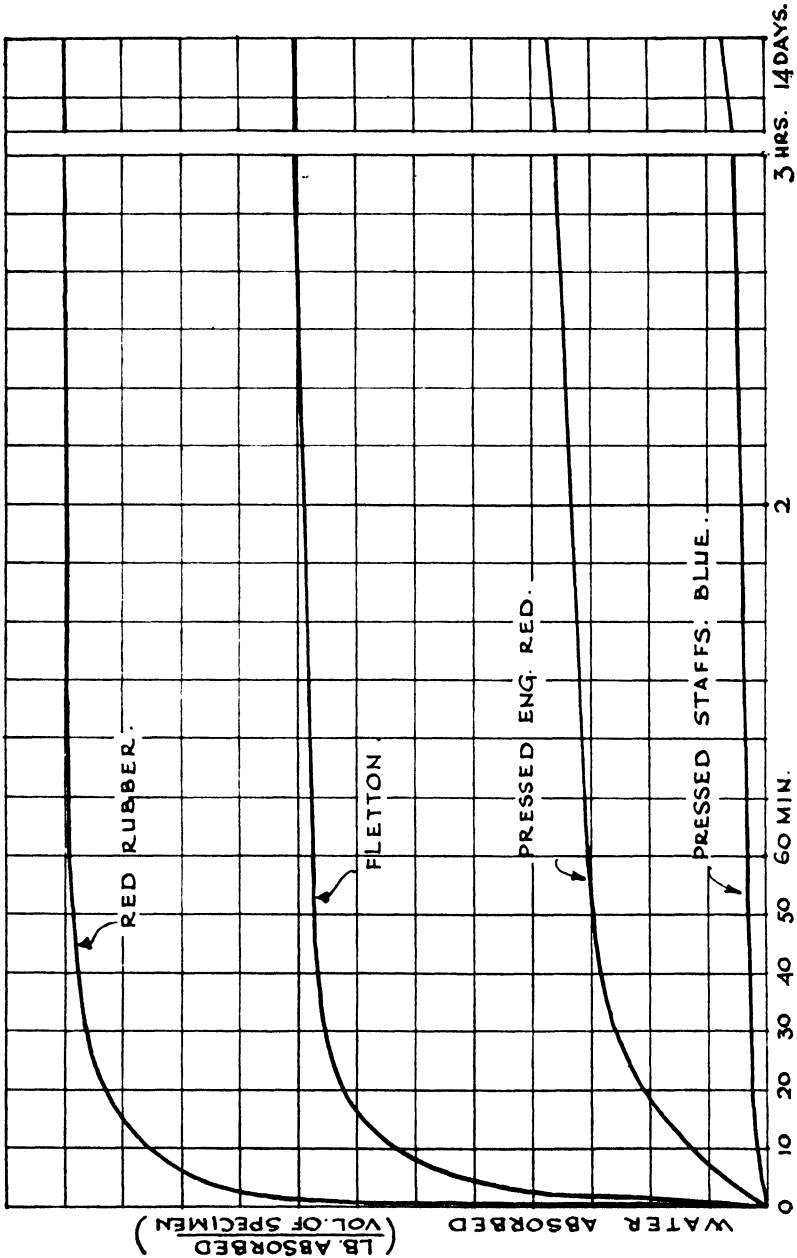


FIG. 50.—Rate of Absorption of Water by Bricks

If the specimens vary in size by more than a small margin the results should be plotted as absorption per unit of volume, say per c.ft. Each result would then be :—

$$\frac{\text{Weight of water absorbed}}{\text{Volume of specimen.}}$$

Having obtained the total absorption of each specimen, either direct or at the end of the above experiment, it is convenient as a further comparison to calculate the *saturation coefficient* of each. If all the voids become filled with water the coefficient is 1, but in most cases it will be less than this. It is determined as follows :—

$$\text{Saturation Coefficient} = \frac{\text{Volume of water absorbed}}{\text{Volume of voids.}}$$

For instance if the volume of voids in our specimen is .033 c.ft. (obtained as the result of Experiment 36) and the volume of water finally absorbed is .029 c.ft. the coefficient will be :—

$$\frac{.029}{.033} = .88$$

It can be shown that the rate of drying out of these bricks bears approximately the same relationship to each other as their rates of absorption. A material which absorbs water quickly therefore dries out quickly, and one which absorbs water slowly takes much longer to dry out.

But it may be held that in practice bricks, tiles, etc., are not immersed in water, but are only exposed to rain and damp air on the surface, usually only one surface. This may be so but it will be found that their comparative behaviour under these conditions is approximately the same.

We have seen that the voids in a porous material act as capillary paths and enable moisture to enter the body of the material. This can be demonstrated simply by standing a red "rubber" brick on end in shallow water, the saturation line in the brick rising at a visible rate. To compare materials for degree of absorption by capillarity each specimen is stood on its face, preferably the face which is normally exposed to the weather, in a shallow dish or tray of water on the flat pan of the 14-lb. scales. (For convenience in this experiment the general rule may be waived and the decimal weights placed in the other pan.) The specimen, whose dry weight has already been determined, is removed at intervals, and the remaining water weighed. The weight of water absorbed at each increment is therefore found by subtraction; this is easier than weighing the specimen itself each time. (Fig. 51.)

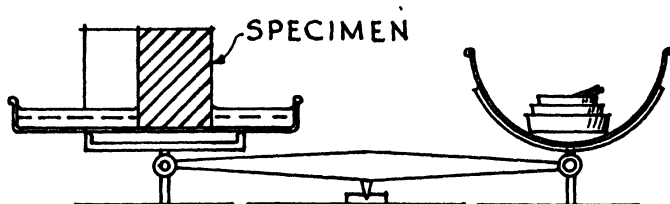


FIG. 51.—Determining Rate of Absorption by Capillarity.

EXPERIMENT 38.—To compare the rate of absorption, by capillarity, of bricks.

	<i>Red rubber</i> Surface area 44·8 sq.in.	<i>Fietton</i> Surface area 24·03 sq.in.	<i>Pressed Eng.</i> Surface area 26·7 sq.in.	<i>Staffs. Blue</i> Surface area 26·6 sq.in.
Dry weight	.. 11·98 lb.	5·32 lb.	9·04 lb.	9·39 lb.
After 2 mins.	.. 12·54 "	5·52 "	9·04 "	9·39 "
" 4 "	.. 12·73 "	5·56 "	9·04 "	9·39 "
" 6 "	.. 12·98 "	5·58 "	9·04 "	9·39 "
" 8 "	.. 13·02 "	5·6 "	9·05 "	9·39 "
" 10 "	.. 13·05 "	5·62 "	9·05 "	9·4 "
" 20 "	.. 13·16 "	5·78 "	9·05 "	9·4 "
" 30 "	.. 13·27 "	5·92 "	9·05 "	9·4 "
" 40 "	.. 13·38 "	6·05 "	9·06 "	9·4 "
" 50 "	.. 13·44 "	6·14 "	9·06 "	9·4 "
" 1 hr.	.. 13·46 "	6·19 "	9·06 "	9·4 "
" 1½ "	.. 13·54 "	6·23 "	9·09 "	9·4 "
" 2 "	.. 13·57 "	6·27 "	9·15 "	9·4 "
" 2½ "	.. 13·58 "	6·38 "	9·18 "	9·41 "
" 3 "	.. 13·59 "	6·39 "	9·21 "	9·41 "
" 24 "	.. 13·6 "	6·39 "	9·27 "	9·41 "
" 2 days	.. 13·6 "	6·39 "	9·29 "	9·42 "
" 7 "	.. 13·6 "	6·4 "	9·3 "	9·5 "
" 14 "	.. 13·6 "	6·4 "	9·3 "	9·59 "

The results are expressed as absorption per sq. in. of wetted surface thus :—

$$\text{Absorption per sq. in.} = \frac{\text{Total incremental absorption}}{\text{Area of surface.}}$$

The graph, Fig. 52, gives the curves for the above results.

A more accurate procedure is to use the apparatus shown in Fig. 53. Here the face only of the specimen is in contact with water, a condition more closely resembling those met with in practice.

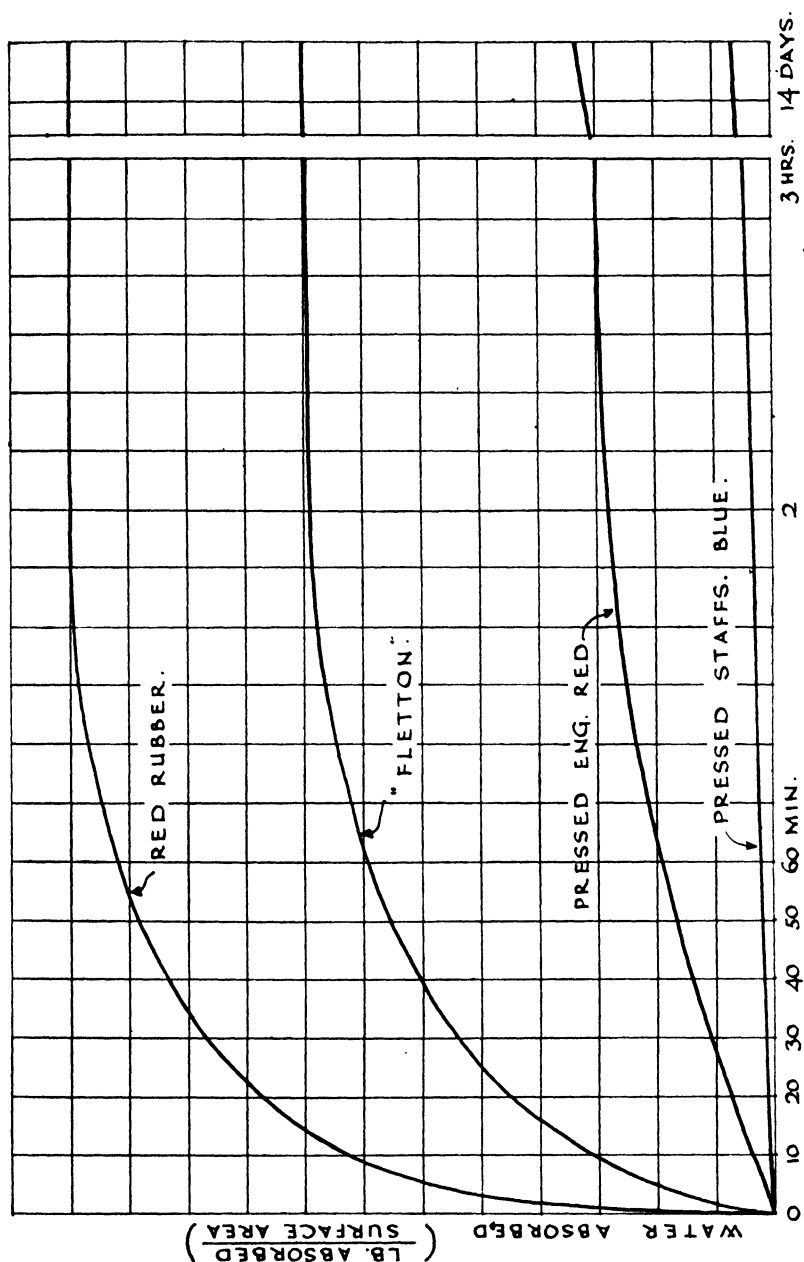


FIG. 52.—Rate of Capillary Absorption of Water by Bricks.

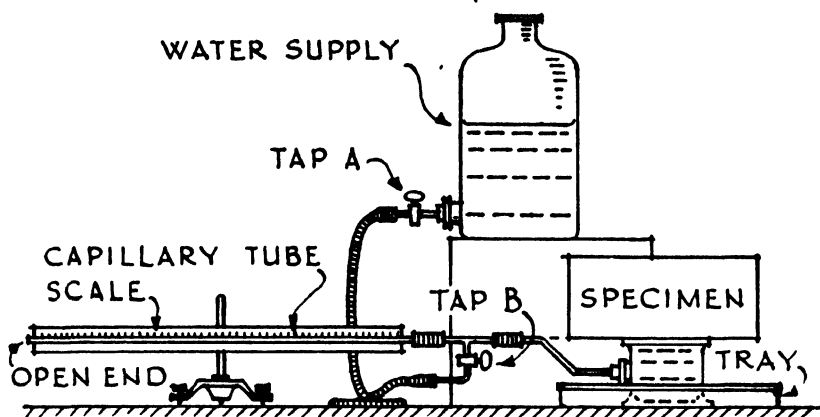


FIG. 53.—To Compare Rates of Absorption of Water.

**EXPERIMENT 39.**—To compare specimens for absorption by capillarity.

Taps A and B are opened, so admitting water to the open topped glass vessel and to the capillary tube until both are just full. Tap B is then closed and the water now stands at the same level in both tube and vessel, with no pressure from the water in the supply flask. The specimen is now placed on the ground rim of the glass vessel, and any absorption is made evident by the movement of the meniscus along the capillary tube from the open end. The face of the specimen should be wetted before placing on the vessel to minimize the risk of entrapped air preventing the whole area covering the vessel being in contact with the water, but apart from this the specimen should be dry. The distance moved by the meniscus in cms. is measured against time and the result expressed as a velocity, the mean of a number of readings. Not the least advantage of this test is the fact that the area of the wet surface is identical for all specimens, this obviating the necessity to calculate absorption per unit of surface area.

The full significance of the property of absorption in connection with building materials will be developed in a later volume, but it may be mentioned here that many difficulties of weathering and decay due to physical and chemical action arise out of the fact that certain materials are porous and so permit absorption.

Weathering and decay may be due to the action of frost, since water contained in the voids near the surface expands on freezing and may thus loosen or burst off surface particles of the material. The moisture absorbed by facing materials is by no means pure water, especially in urban districts. Rain is a powerful solvent and in such cases, especially in industrial towns and cities, it dissolves various gases to become a dilute acid the effect of which in the pores of some materials is to cause chemical action and consequent disintegration. The phenomenon usually

called "efflorescence" is also rendered possible by reason of porosity, for the efflorescence or "scum" is composed of minute crystals of various salts deposited at the surface of the wall by the evaporation of solutions drawn to the surface from the interior of the material through the pores in the process of drying.

The absorption of water by a dry, porous material is mainly by capillarity until the water has reached another face, usually the opposite one. Capillarity then ceases since there are no further pores to become filled, but water can still pass through the material under the action of gravity or pressure. The passing of water *through*, as distinct from *into* a material is referred to as *permeability* instead of absorption, and materials which do not permit this are called *impervious* materials.

**MOISTURE CONTENT.**—The amount of moisture which a material contains at a given time is called its moisture content. It may vary at different times for several reasons, deliberate or fortuitous. For instance timber in the growing tree contains a very high percentage of moisture in the form of sap which must be reduced by seasoning before the timber is fit for use. Building stone in the quarry contains moisture, "quarry sap," which evaporates from the surface and in some cases results in the formation of a harder skin which enables the stone better to resist decay. It also makes the stone more difficult to dress; consequently such labours as moulding, carving, etc. are done as soon as possible after quarrying. If left until the protective coating has formed, not only will the work be more arduous but this weather-resisting coating will be destroyed and the life of the stone reduced. Concretes and mortars require water for their preparation, only a small proportion of which is necessary for the action of setting; the remainder is left as free moisture most of which afterwards dries out. Bricks, tiles and other fired materials naturally contain no moisture immediately after manufacture, nevertheless they soon acquire some from contact with the atmosphere.

Apart from the presence or absence of this initial moisture all porous building materials contain "hygroscopic" moisture. If the material contains a high percentage of moisture and the surrounding air is dry, the material tends to lose some of its moisture by evaporation. Conversely, if the material is dry and the air moist some moisture will be absorbed from the air. The materials are in this way always tending to maintain a condition of moisture equilibrium, with the atmosphere when used externally, or with the air conditions inside if used for internal work.

The amount of this acquired moisture affects certain properties of materials, for instance strength is reduced with increase of moisture, but



usually it is the constant change of moisture content due to changing weather conditions which may be detrimental either to the material itself or to the item of construction in which it is employed.

Although the effects of these alternations of moisture content are a source of trouble in connection with all porous building materials it is only in the case of timber that it is essential to know the exact percentage of moisture present. This governs the suitability of the wood for a given purpose under given conditions of temperature and dryness.

To determine the moisture content the specimen should be small, say  $\frac{3}{8}$ -in. square and 2-in. long, otherwise it will take too long to dry. The specimen is weighed and then dried by placing in a water oven, or failing this it may be dried in a heated store. Fig. 54 shows a water oven, which has the advantage of convenience and control of temperature and ventilation. It is made of copper and is jacketed so that the water vapour entirely surrounds the oven proper. Ventilation is through an adjustable grille in the door and out through an outlet in the top. The temperature should not exceed 100 deg. Cent. The specimen is removed after 1 hour, reweighed and returned to the oven, this being repeated until no further decrease in weight is noted. The specimen is then dry and its weight is its "oven-dry" weight. The calculation for obtaining the free moisture content is given on the following page.

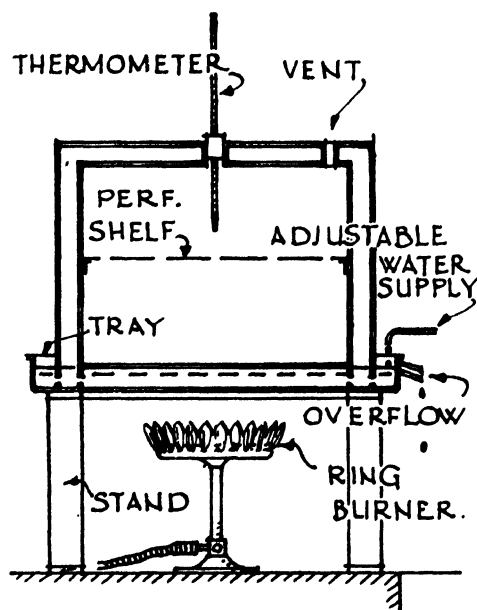


FIG. 54.—Water Oven for Controlled Drying of Specimens.

EXPERIMENT 40.—To determine the free moisture content of timber.

Initial weight of specimen	= 15.27 gm.
Oven-dry " " "	= 13.76 gm.
Therefore Loss in weight = 15.27 — 13.76	= 1.51 gm.

This equals weight of moisture driven off, and the result is expressed as a percentage thus :—

$$\begin{aligned}\text{Moisture content} &= \frac{\text{Initial weight} - \text{Dry weight}}{\text{Dry weight}} \times 100 \\ &= \frac{1.51}{13.76} \times 100 = \underline{\underline{11 \text{ per cent.}}}\end{aligned}$$

Note that the percentage is of the weight *after drying*.

Under the conditions of the last experiment, that is with a moisture content of 11 per cent. or thereabouts, drying would take from 2 to 3 hours. For a specimen of newly-felled timber the time necessary may be from 8 to 10 hours according to the type of timber and according to the number of specimens in the oven at the same time.

The moisture content of newly-felled timber may be anything from 50 per cent. up to 200 per cent., and this is reduced by careful seasoning to about 20 per cent. for general carpentry work and  $12\frac{1}{2}$  per cent. for average joinery (internal). The figure of 20 per cent. for outside work is the average over the year in this country as it varies from approximately 25 per cent. in winter to 15 per cent. in summer. If the timber is drier than this it will absorb atmospheric moisture and swell; if it is wetter it will lose moisture and shrink. The figure of  $12\frac{1}{2}$  per cent. for internal work is based on the average air conditions inside buildings.

In the special case of timbering to receive wet concrete in poured concrete work the timber must not be too thoroughly seasoned or its movement will affect the appearance of the finished concrete.

There are methods of determining the moisture content other than by drying and weighing, but they require special apparatus. One method works on the principle of driving off, collecting and condensing the moisture. Electrical methods are also used but are of more interest to the timber specialist than to the architect or builder.

When, in practice, a sample is to be taken from stock, it should be cut from the interior of a board or plank and not from the outside since wood near to the surface will be drier and not representative. In some cases borings are made and the chips tested but the difficulty then is that they are liable to lose moisture before the initial weighing can be done.

**Porosity related to Surface Texture.**—Some materials, usually those used for facing walls and roofs, are often selected on the score of their visual appearance irrespective of other attributes. It is unfortunate that the materials which "look" best, for instance Cotswold stone,

hand-made bricks and tiles, etc., owe their charm not only to their colours but to their surface texture, for this necessitates a very porous structure which militates against good weathering properties. It is in fact largely to the extent to which they have suffered from weather and vegetation through the years that they owe their attractive appearance. Viewed from a strictly practical viewpoint it can be understood why the charm of the building and the rheumatism of the occupants are so often closely related.

This does not mean that such materials are unsuitable or should not be used ; it does mean, however, that when using them we should bear in mind that adequate precautions are more than usually necessary to ensure that the building construction takes their failings into account.

The surface texture of materials is usually quite a reliable guide to their probable weather resistance, especially if the surfaces are compared by inspection under a magnifier.

**Porosity related to Condensation.**—The question of condensation of moisture is dealt with later, but whilst on the subject of porosity it is fitting to say that it is this which decides whether condensation proves troublesome or otherwise. Everyone has noticed the condensed moisture which collects on the inside surface of window glass in cold weather, and sometimes causes trouble by running down and finding its way into joints in the joinery, so inducing decay. This is due to several causes, chief of which are (a) that the glass is non-porous and of small thickness and is consequently maintained at about the same temperature as the outside air, and (b) that having a non-porous surface the condensed moisture cannot enter the glass to be subsequently dried out when conditions change. In practice a wide, shallow condensation groove allows such moisture to be mopped up, and is better than efforts to permit it to escape to the exterior via holes, since these become blocked or painted up.

**Porosity related to Insulation.**—By insulation we mean the property of a material of resisting the passage of heat and sound through its mass. Both of these questions are discussed fully later, but again we should mention that porosity is once more the chief influencing factor.

So far as the transmission of heat is concerned it is obvious that the heat motion of the molecules of a material (see Chapter I) is more readily transferred to adjacent molecules *et seq.* in a non-porous material than in one containing a high percentage of pore space. The pores are, in the case of a dry material, filled with still air, which permits the passage of heat with great reluctance ; such a material therefore has a high heat insulating value. If the pores are filled with water the insulating value is reduced because water under such conditions of confinement transmits heat much more readily than does air.

A simple experiment to show how different materials vary in their

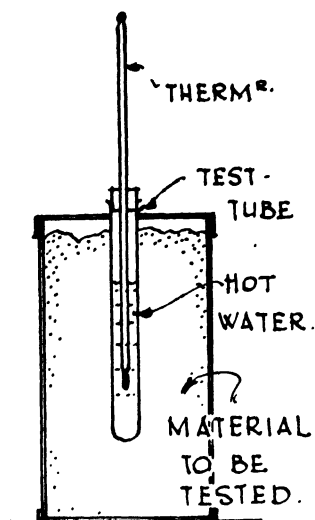


FIG. 55.—Simple Test showing Heat Loss affected by Porosity.

heat insulating property is to take a number of tin containers of equal size, make a hole through the lid of each of such size as to allow a test tube just to pass through, and fill the space around the tube with the material to be tested. Fill the test tube with hot water, fit a one-hole rubber bung and thermometer, and commencing from the same temperature in each case, note the rate at which it decreases due to heat lost to the surrounding material. Convenient materials are air, sawdust, concrete and timber. The concrete should be made with granite chips or gravel not exceeding  $\frac{1}{4}$ -in. across and can be cast in the tin with the test tube in position. For timber a piece should be turned down to correct diameter and a deep hole bored in the top to take the test tube.

EXPERIMENT 41.—To compare materials for heat insulation.

#### READINGS FOR MOIST CONCRETE.

Time	Temp. Cent.
Zero .. .. .	70 deg.
After 1 min. .. .. .	61
„ 2 „ .. .. .	55
„ 3 „ .. .. .	50
„ 4 „ .. .. .	46
„ 5 „ .. .. .	43
„ 6 „ .. .. .	40
„ 7 „ .. .. .	38
„ 8 „ .. .. .	35.5
„ 9 „ .. .. .	34
„ 10 „ .. .. .	32
„ 15 „ .. .. .	25.5
„ 20 „ .. .. .	21
„ 30 „ .. .. .	16

In the case of sound, little need be said at this point except that sound is absorbed into a porous material but is reflected from a non-porous one. To realise the truth of this one has only to compare the experience of singing in the bathroom and again in the drawing-room, or to recall the contrasting sensations of sound on entering a swimming bath hall and, say, a furniture showroom or theatre foyer. Further, the sound energy itself, like heat, travels more readily from molecule to molecule through a dense medium than a porous one.

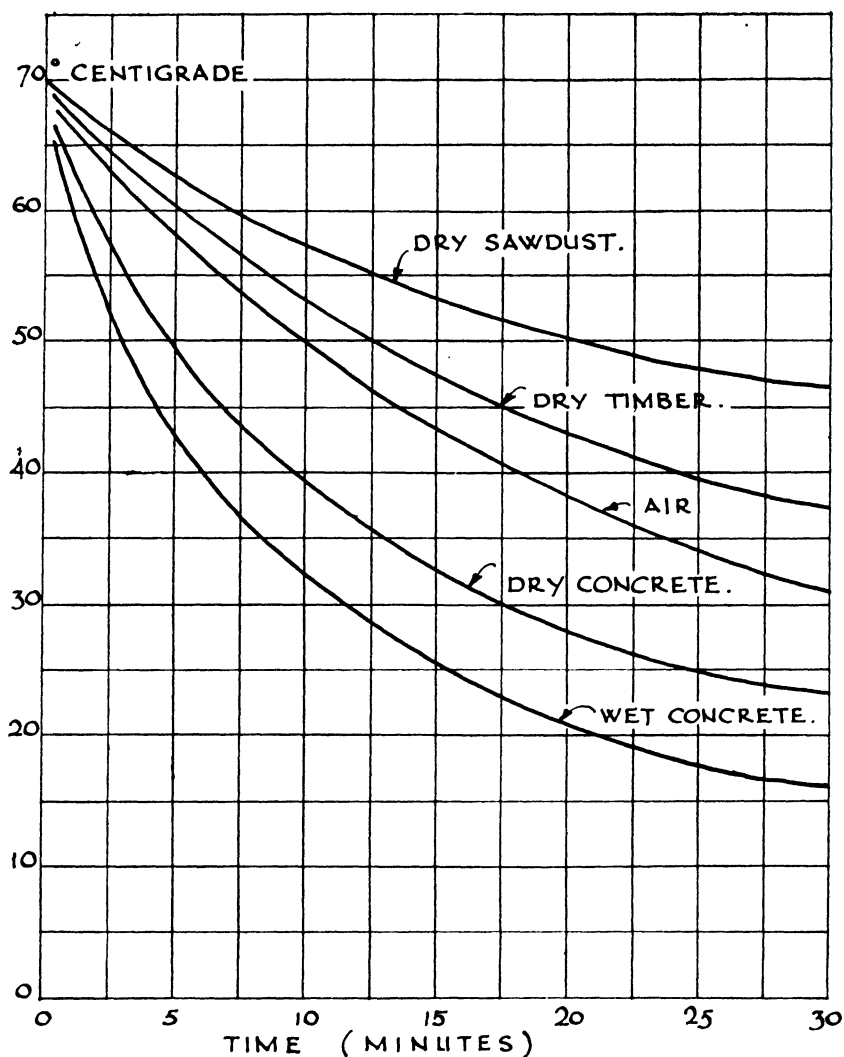


FIG. 56.—Comparative Rates of Heat Loss through Materials.

### 3. IMPERVIOUS MATERIALS.

The differences in the behaviour of porous and non-porous materials are now apparent. We can say, then, that an impervious material is dense and usually strong, it does not permit water to enter or pass through it, it is not subject to weathering, decay or efflorescence, but it is lacking in surface texture, it readily permits the passage of heat and sound, it favours condensation, and does nothing towards rendering it less evident.

The most important property is its high resistance to the penetration of moisture, and this is why we generally refer to it as impervious rather than non-porous.

There are three chief ways in which moisture may gain admittance to building materials from the outside, apart from accident or defective construction.

- (a) by rain soaking downwards into copings, roofs, etc. This is effected by capillarity assisted by gravity and perhaps to a smaller degree by wind pressure.
- (b) by moisture soaking upwards through walls, surface concrete, etc., by capillarity alone.
- (c) by water in contact with the face of a wall soaking inwards. This is due to capillarity together with external wind or soil pressure or internal evaporation.

**Damp-proof Courses.**—In cases (a) and (b) it is usual to employ impervious materials in the form of a layer so placed in the construction as to constitute a barrier to the further movement of moisture and its possible access to the interior of the building. Such a layer is called a *dampcourse* or *damp-proof course* or *D.P.C.*

Though the testing of materials for permeability is deferred until a later volume, the common forms of D.P.C.s will be described, together with their methods of use.

**SHEET METAL D.P.C.s.**—Copper and lead are both in use as D.P.C.s. They are wholly impervious to moisture and do not fracture with unequal settlement of the wall. They are inconspicuous owing to their small thickness, and the fact that they are obtainable in great lengths means that joints are few, the joints in any D.P.C. being more vulnerable than the material itself as a rule. Copper is on the whole more suitable than lead as lead is liable to corrode by contact with the lime in mortar.

**COMPOSITE ROLL D.P.C.s.**—Bitumenized felt is a felt treated with bitumen so as to permeate it thoroughly and give an impervious, flexible sheet. It is produced in long rolls and its surfaces are sanded to give adhesion to the mortar, to prevent sticking when rolled and to prevent sliding under lateral pressures, as in a retaining wall. In better class D.P.C.s a layer of fibre, stout canvas, or lead is sandwiched between two layers of the felt. These types of D.P.C. are proprietary and vary considerably in efficiency, some being excellent and others not likely to have a very long useful life. The best kinds have the advantages of sheet metal D.P.C.s without their disadvantages, and are possibly the best all-round type.

**ASPHALT D.P.C.s.**—Asphalt is poured whilst hot and consequently has no actual joints. This, together with the fact that it is absolutely

impervious and adheres well to the brick or stonework, are advantages. Its disadvantage is that the thickness necessary to act satisfactorily as a bedding material, although unobtrusive in work, means that under pressure and in hot weather it is liable to squeeze out.

**SLATES IN CEMENT.**—The slates must be specially prepared for the purpose, of full wall thickness, and laid in two courses in a strong cement mortar, bonded as in stretcher bond. Old roofing slates should not be used as they contain nail holes and may possibly be defective from long service. They should be pointed neatly flush with the wall face and the D.P.C. then looks well, although more conspicuous than the previous types. The disadvantage is the fact that the slates are brittle and sometimes crack in cases of settlement.

**BLUE BRICKS IN CEMENT.**—Usually in two courses properly bonded they are very effective, but are unsightly. Where they are used at the base of a wall it is better to construct the wall in blues from ground level up in the form of a plinth. Some of the red engineering pressed bricks or brindles are as impervious as blues and have a rather better appearance.

**TESTING D.P.C.s.**—Most of these types of D.P.C. are easily tested in the laboratory by building up a small pier 3 courses high and one brick in each course. They are placed in a shallow tray of water, and any rise of moisture through them indicated by anhydrous copper sulphate.

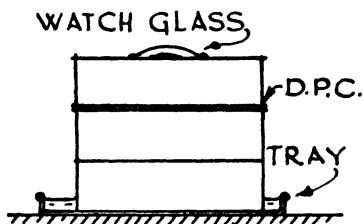


FIG. 57.—Rise of Moisture through Bricks.

This is prepared from copper sulphate crystals by heating and drying, which reduces them to a fine, white powder. On coming into contact with moisture, however little, it commences to regain its former blue colour. It is spread on the top of the pier and covered by a glass, sealed around the rim to prevent access of atmospheric moisture. One pier should be tested without its D.P.C.

**USE OF D.P.C.s.**—As important as the composition of D.P.C.s is the question of where they shall be placed. A horizontal D.P.C. near the base of walls to check rising dampness is now universally used, although its efficiency is often impaired by its being placed too near to ground level, or by the subsequent laying of paving bringing about a similar result.

Although building authorities insist on the provision of a D.P.C. at the base of walls they are not so insistent upon the effective sealing of the ground itself. In consequence we find all too often that no provision whatever is made for the prevention of the entry of ground air into the

space beneath hollow ground floors, or for the proper proofing of solid floors. The one is not a whit less important than the other, for if a site is of such a character as to necessitate the first, the second provision must be equally necessary. In many cases where concrete is laid over the underfloor area it is apparently considered that inferior stuff will do, since it carries little load. The fact is that it should be better than

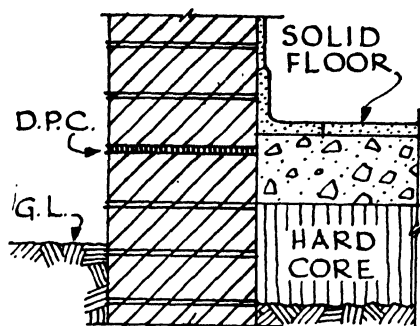


FIG. 58.—D.P.C. in Solid External Wall—Solid Floor. (D.P.C. should be near Top of Floor.)

load-bearing concrete, for a more porous material than an overwet and weak concrete mix would be difficult to find. It is a pity that the ill-effects upon the building and its occupants of such a state of affairs is not so immediately apparent as they would be if the same attitude were adopted towards the roof. Figs. 58 to 62 show suitable arrangements for D.P.C.s near to ground level.

A D.P.C. is necessary at all points in the fabric of the building where moisture is liable to find its way through to the interior via the material. The top of a wall needs just as much protection as the base, and there are several instances where a D.P.C. is essential, though not usual. An overhanging eaves is the best protection, but failing this other precautions are necessary.

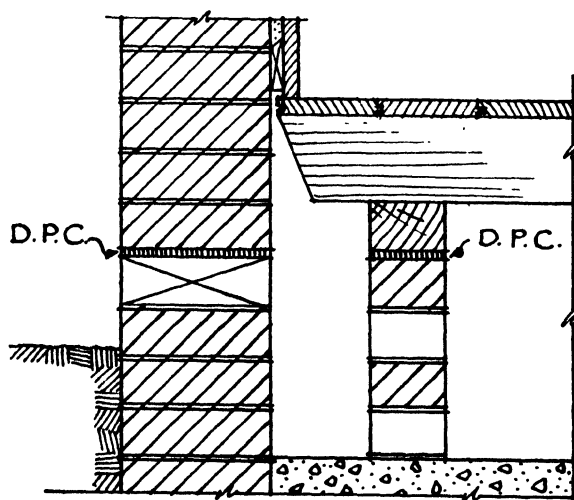


FIG. 59.—D.P.C. in Solid External Wall—Hollow Floor. (Wood Joists should not be built into Wall.)



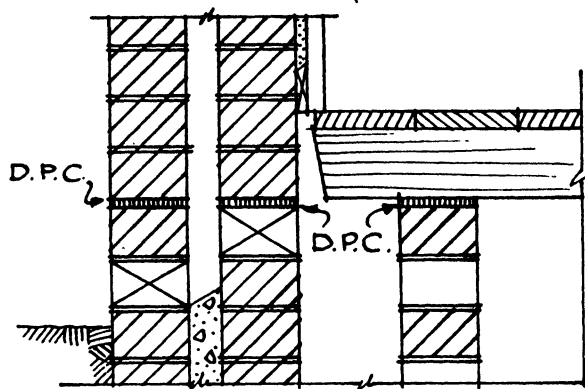


FIG. 60.—D.P.C. in Cavity External Wall—Hollow Floor. (Floor Level independent of Ground Line if built on Sleeper Walls.)

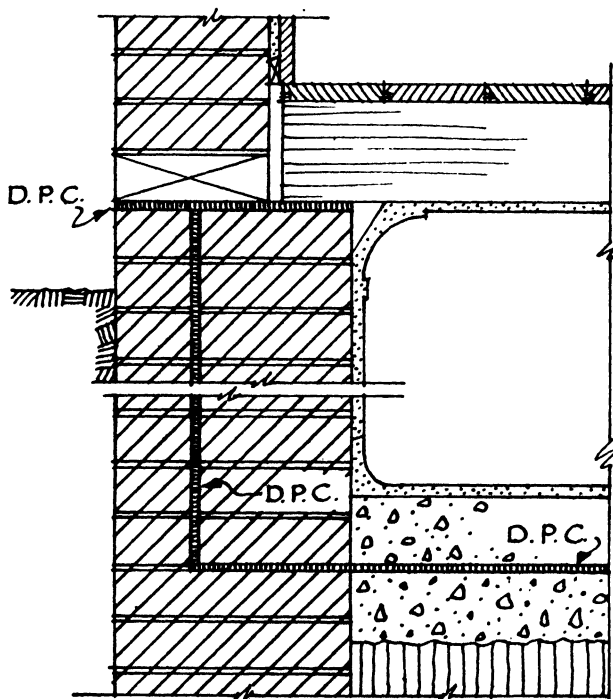


FIG. 61.—D.P.C. in Solid External Wall with Basement. (D.P.C. must be continuous.)

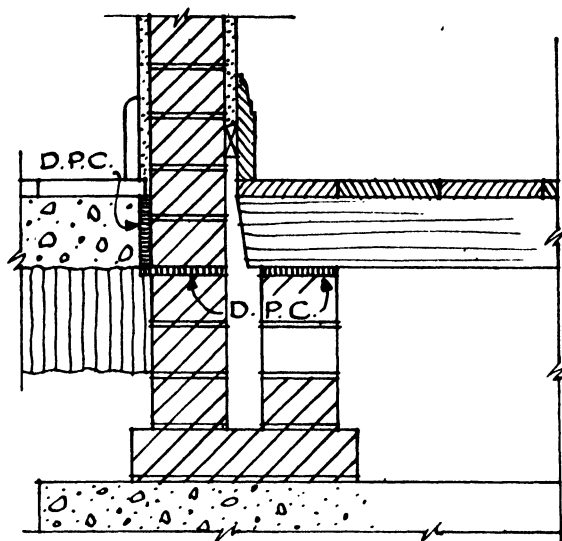


FIG. 62.—D.P.C. in Internal Wall—Junction of Solid and Hollow Floors.

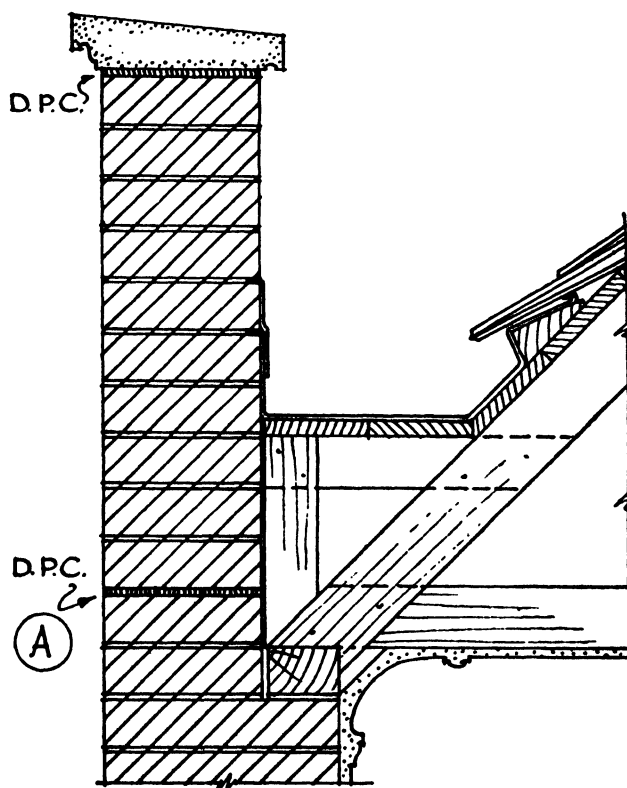


FIG. 63.—D.P.C. to Parapet Wall.

Whilst a good type of coping may be sufficient for a boundary wall it is not good enough in the case of a parapet wall. A horizontal D.P.C. should preferably be inserted beneath it, and in any event one is necessary at A in Fig. 63. The wall just below point A is especially liable to dampness because the parapet wall is exposed to the weather on the back as well as the front face, and is seldom more than one brick thick. In the case of a flat roof the area of back exposed is greater still.

Another position in which no provision is usually made to arrest the downward penetration of rain is the chimney stack. This is the most exposed portion of the building, often with half-brick walls only, but with a comparatively extensive area exposed to rain from all quarters. The water absorbed sinks by capillarity assisted by gravity, and makes itself evident on the uppermost storey near the ceiling. When a D.P.C.

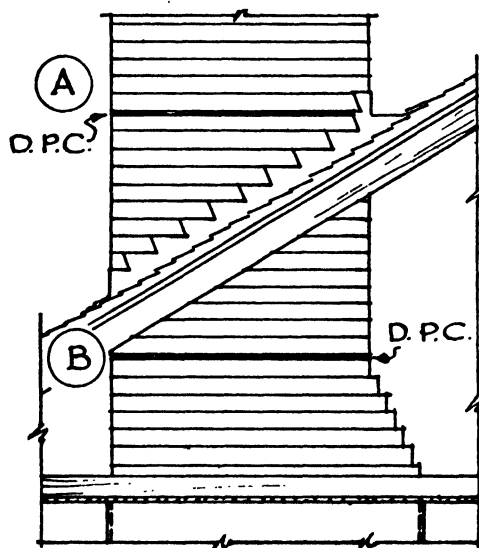


FIG. 64.—D.P.C. to Stack.

is used it is generally placed in position A or B (Fig. 64) but neither is effective in protecting the area of brickwork between the two levels, and in any case once the material above is saturated the excess runs down over the face of the work and so enters the interior. To use both would be more effective but if the brickwork between levels A and B were in impervious brickwork the whole would then become a D.P.C. When the stack is astride the ridge the height exposed is less and the height between roof and ceiling is more; these conditions are therefore not so severe.

The necessity for protecting the head of an opening in cavity wall construction is invariably realised, but the jambs need to be protected too. Building the wall solid for a foot or so from the jamb is not sufficient; the cavity should extend right up to the jamb and be sealed by a vertical D.P.C. The mortar joint immediately beneath the sill is also a vulnerable point, because no rain running down the face of a window can be absorbed until it reaches the sill. The sealing of the cavity around the opening should therefore be completed by inserting a D.P.C. in this joint.

#### 4. MOISTURE MOVEMENT OF MATERIALS.

Materials may suffer change of volume in two principal ways :—

1. As the result of the application of force.
2. By lack of stability in relation to the physical conditions in which they are placed. This may be subdivided into :—
  - (a) By a change of temperature.
  - (b) By alteration of moisture content.

It is now with 2 (b), change of volume with change of moisture content, that we are concerned, and in this first volume our study will be confined to the building material which is by far the most susceptible, timber. Timber products will not be included here.

**Timber.**—Building timbers all belong to a botanical group of plants called *Exogens*. This means that the tree grows by the successive formation of layers of wood each encircling the previous ones beneath the bark. The layers are composed of long strings of elongated cells, side by side and in the direction of the length of the trunk or branch. Except in the heartwood near the centre of the tree these cells contain sap, which is water containing various solutes, and the walls separating the cells are composed of strands of fibre rather like wool. These also are saturated.

During seasoning, or when subsequently absorbed moisture dries out, the cell cavities themselves lose their moisture first. The effect of this is merely to reduce the weight or density of the timber, and this stage of drying (the cells being dry but the cell walls remaining saturated) is called the *fibre saturation point*. When this point is reached the moisture content is usually 25 per cent. to 30 per cent., and *it is only when the moisture content fluctuates below fibre saturation point that moisture movement occurs*.

During the early stages of drying, until this point is reached, the density of the timber and its moisture content decrease together. The density of softwoods may be reduced by 20 per cent. in this way, but below fibre saturation point the decrease is less because the volume also is decreasing. Actually, below this point, each 1 per cent. change in moisture content is accompanied by about  $\frac{1}{2}$  per cent. change in density.

**TIMBER AS A GEL.**—In Chapter I, under “Colloids,” we referred to *gels* and to the fact that they all expand and contract with alteration of water content. Gelatin, glue, etc., are called *non-rigid gels*, timber and other materials of similar fibrous composition such as cotton and wool are called *rigid gels*. Brick, stone, concrete, etc. also behave like rigid gels, but they are rather different in their mechanical rigidity, and this affects their behaviour. These materials, as well as the amorphous

non-rigid gels, are more or less homogeneous in structure and consequently swell and shrink in volume uniformly in three dimensions, but this is impossible in the case of timber, etc. on account of their different structure. The longitudinal chains of cells in timber are somewhat similar in arrangement to the strands of wool and other natural fibres.

**SORPTION.**—We must now explain why it is that gels are unstable in the presence of moisture. Water can be associated with other substances in various ways. It can be combined by chemical action so that new substances are formed; thus one molecule of quicklime (calcium oxide) joins one molecule of water to form one molecule of slaked lime (calcium hydroxide). It can be associated in solution; thus if there are more molecules of water than of quicklime we get slaked lime as before, but the excess of water dissolves this and gives us a solution of slaked lime (lime water). We have also seen that water can be associated by capillarity so as to remain “free” water; water in a capillary tube is united to the glass by a purely physical bond. Water can be associated with the molecules of a salt as water of crystallization.

There is, however, a further way in which water and a solid may unite, viz., by *sorption* (not to be confused with absorption). It is sometimes referred to as a “loose” chemical bond, and the condition is in fact someway between true chemical and physical bond. The molecules of water become attached to those of the solid and so increase its volume, but the accompaniments of chemical action are absent. In the case of timber they attach themselves to the molecules of the fibres which form the cell walls, and therefore produce expansion “across the grain.” The amount of longitudinal expansion is negligible by comparison.

It has been found that when timber is completely saturated the amount of water held by sorption (sorbed water) is roughly 20 per cent. of the dry weight; the remainder is free water held merely by capillarity.

#### EXPANSION AND CONTRACTION OF TIMBER.—

Fig. 65 shows diagrammatically a cross section through a log, and is given to indicate the two main directions of cross-grain moisture movement. These movements take place concurrently but are not of equal amount. Table 4 gives the percentage shrinkage during drying

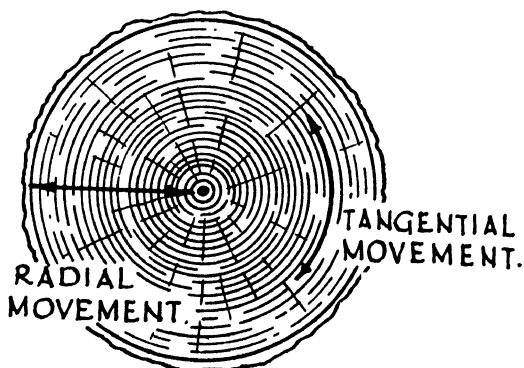
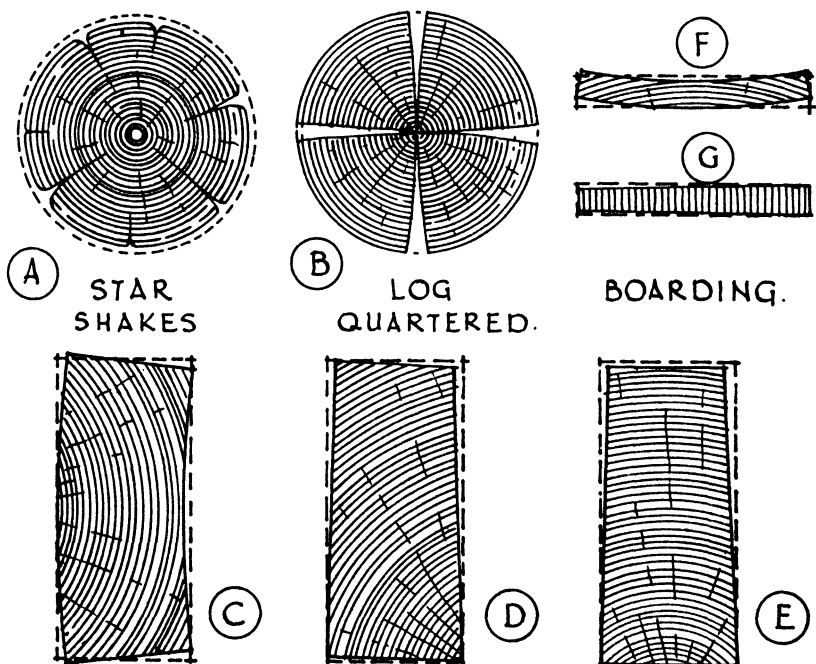


FIG. 65.—Directions of Cross-Grain Moisture Movement in Timber.

out from the dimensions when unseasoned, for some of the woods in common use. The figures are from various authorities and they explain the inability of wood to maintain its dimensions and shape under conditions of varying moisture content. It must be remembered that longitudinal movement, though comparatively slight, contributes also to this difficulty.

TABLE 4.

<i>Timber</i>	<i>Lineal shrinkage per cent.</i>	
	<i>Radial</i>	<i>Tangential</i>
English Ash .. ..	4.8	11.8
„ Beech .. ..	3.5	8.5
Honduras Mahogany ..	3.4	4.7
English Oak .. ..	2.7	7.3
Red Deal .. ..	4.1	6.6
Oregon Pine .. ..	4.1	7.1
Teak .. ..	2.3	3.3
Western Red Cedar ..	2.1	4.2



RECTANGULAR BEAM SECTIONS.

FIG. 66.—Effects of Moisture Movement upon Timber Sections.

Let us study in Fig. 66 some of the effects of this differential movement, and at the same time identify in Fig. 65 the position of each section shown.

In all cases the dotted lines indicate the original shape of the section. A shows the effect of seasoning the uncut log ; the whole section shrinks but the tangential shrinkage of the outer portion, which dries out before the interior, sets up stresses which cause the radial splits known as "star shakes." B shows what happens when the log is quartered first. This obviously has the effect of reducing star shakes to a minimum. At C, D and E are shown rectangular sections, which indicates that from the viewpoint of remaining true to shape E is the best arrangement. F and G show board sections and indicate the necessity for "standing grain" in such cases to prevent cupping.

**CUPPING.**—Cupping is the term used to denote the curvature assumed by wood when used in scantlings of which the width is much greater than the thickness. It usually occurs owing to the disposition of the grain in the cross section, but there is a contributory factor known as *casehardening*. Casehardening is not a property of the timber ; it arises from the treatment received during seasoning or drying. Moist wood is not so rigid or hard as dry wood. If wood is treated with steam so that it becomes hot and moist it may be bent within certain limits. If it is then allowed to cool and dry it retains its curvature, but is in a state of permanent internal stress.

If a converted section such as a deal or plank is dried too rapidly the moisture evaporates first from the outer layers, at a faster rate than that in the interior can take its place. The contraction of the dried outer layers is resisted by the interior wood which is still moist, resulting in a state of tension in the outer layers and a state of compression in the interior. The outer layers become rigid whilst under tension and this prevents the normal shrinkage of the interior as it, in turn, slowly dries. After drying is complete the interior portion now comes under tension and outside under compression, and if the deal is subsequently sawn through, the interior tension is relieved by the inner faces becoming concave, and the exterior compression is at the same time relieved by convexity developing on the outer faces. Thus, although the original deal was possibly not distorted, it was in a state of stress which only produced a visible effect on sawing it into thinner boards.

Where cupping is due to this cause it can be remedied by steaming and softening the outer surface, so getting rid of the stresses which produced the curvature. Its prevention lies in careful and controlled drying of the larger sections from which the scantlings are cut.

Fig. 67 shows how, in the case of boarding, the disposition of the grain affects the efficiency of the construction (apart from the question of casehardening).

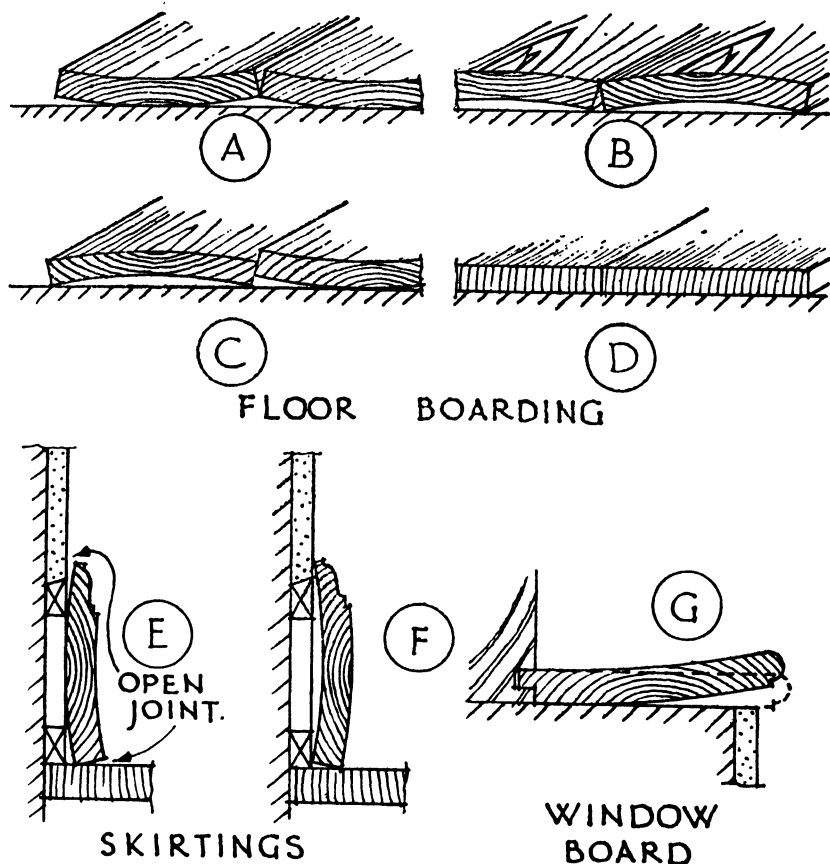


FIG. 67.—Effects of Grain Direction in Wood Boards.

Boarding for floors and flat roofs is frequently specified to be laid “heart side down” as at A. The idea behind this requirement is to prevent shelling or peeling at the points shown by blacker lines at B, but the sharp ridges caused by the cupping of the boards readily cut into linoleum and sheet lead and reduce their life. The arrangement at B is to be preferred except for positions where the boarding is to remain uncovered and shelling would be troublesome, such as in a table top or floor. Where tongues and grooves allow it the boards may be laid as shown at C, but the only way of obtaining a satisfactory job is to use boards with standing or vertical grain as at D.



At E and F (Fig. 67) are shown two skirting boards. The first invariably produces open joints as shown, whereas the second, heart side outwards, is really better in this position than if the board were straight grained.

G shows one of the troubles associated with wood window boards. This is an instance where a board having standing grain should always be used. Such boards are sometimes termed "rift-sawn."

All the effects discussed here have been due to the timber losing moisture. When timber is too well seasoned and is subsequently put into a moist situation, as in a building in progress, the reverse happens.

**FRAMING.**—The framing of doors, wall panelling, and similar wood construction of great extent was the old-time craftsman's way of overcoming these difficulties. The styles, rails, etc., of the framing are of very small dimensions of section as compared with their length, so that the cross-grain movement is negligible. They are framed together so as to leave the majority of the area as openings into which are fitted panels, usually as narrow as possible in relation to their height, not fixed in any way but free to expand and contract within the limits of the frame, otherwise they split upon shrinking or buckle upon swelling. Later, in the 18th century, fashion demanded much more extensive panels, and boards had to be joined edge to edge to provide them. The methods of ensuring that the large panel acted as a unit in the matter of movement are given in books on Building Construction or Joinery, and involve the use of rear battens to which the boards are fixed so as to permit of slight movement. Nevertheless most original work of the period can show some of the panels split from top to bottom through the inefficiency of the precautions taken. Nowadays, built-up boards have solved this particular difficulty.

**TESTING MOISTURE MOVEMENT OF TIMBER.**—If we wish to measure the moisture movement of timber, or compare different kinds, all that is necessary is some arrangement whereby the length of a specimen can be measured before and after the change of moisture content. Expansion due to wetting is more conveniently shown than contraction due to drying, and a large specimen obviously gives greater accuracy, but the arrangement for wetting it thoroughly during the test introduces a difficulty. The apparatus illustrated in Fig. 68 permits a specimen just over 10-in. long to be tested and although the actual expansions are small they are magnified by the apparatus some 1,024 times.

**EXPERIMENT 42.**—To measure the moisture movement of timbers.

Referring to Fig. 68 the specimen, about  $\frac{3}{4}$ -in. wide,  $\frac{3}{4}$ -in. thick and 11-in. long is clamped between the two metal bars. It is securely held near one end by the two points or knife-edges, whilst near the other end, 10-in. away, are two small diameter brass rollers,

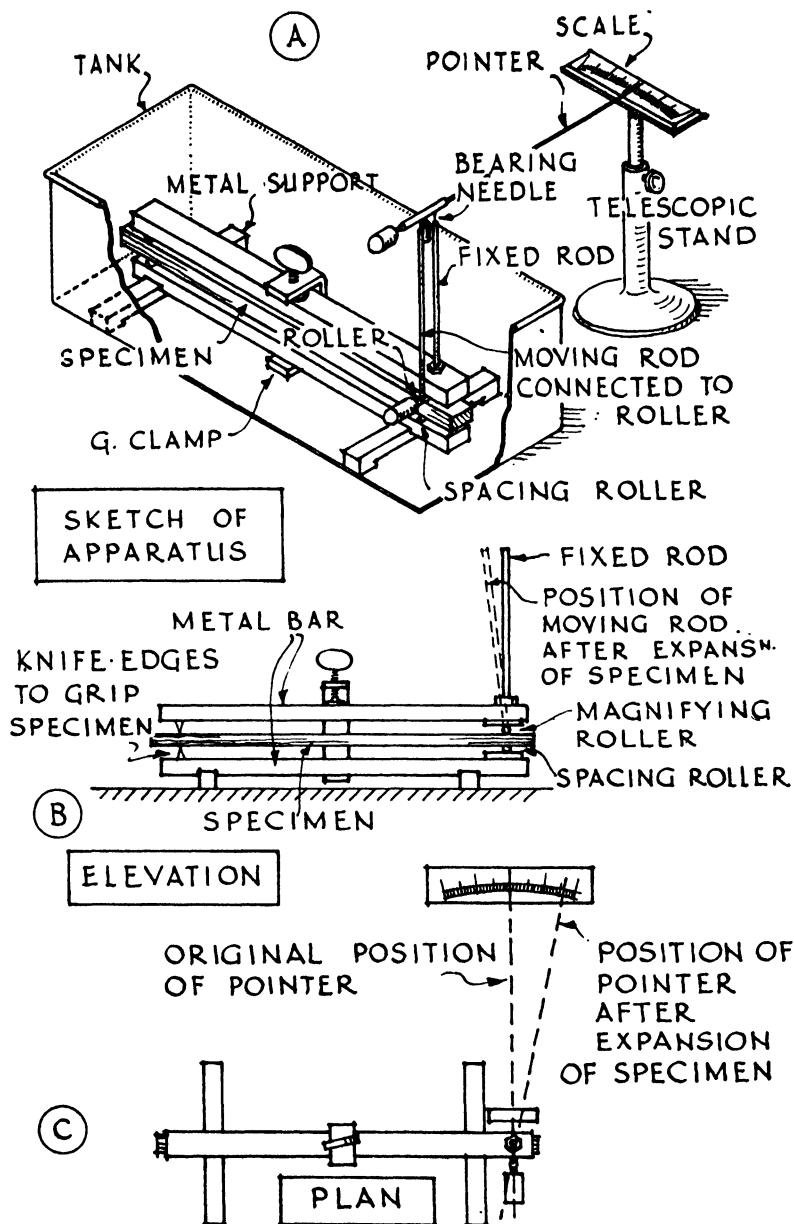


FIG. 68.—To Compare Moisture Movement of Materials:

one merely for spacing and the other connected to a vertical rod. A second vertical rod is fixed alongside it by screwing down to the upper metal bar. When the specimen expands upon absorbing water its expansion turns the two rollers, since its other end is fixed, and the effect of this on the vertical rods is shown in the sketch at B. The roller and rod magnifies the expansion  $\times 64$  and the top of the moving rod has moved this amount relative to that of the fixed vertical rod. The horizontal pointer is balanced on the two rods by needles fitting into holes in the tops of the rods and at C is shown how the movement of the moving rod is again magnified by the pointer  $\times 16$ . The movement of the tip of the pointer over the scale is therefore  $64 \times 16 = 1,024$  times that of the moving end of the specimen, and a reading of 1-in. indicates an expansion of  $\frac{1}{1024}$ -in.

The specimens are most conveniently end-grain, but cross-grain specimens can be tested if small strips of thin tin plate are inserted to protect the wood where it is gripped by the points and the rollers.

The graph, Fig. 69, shows the rate of expansion of different specimens obtained with the apparatus. The complete test of end-grain specimens is a rather lengthy procedure as most of the absorption takes place via the ends.

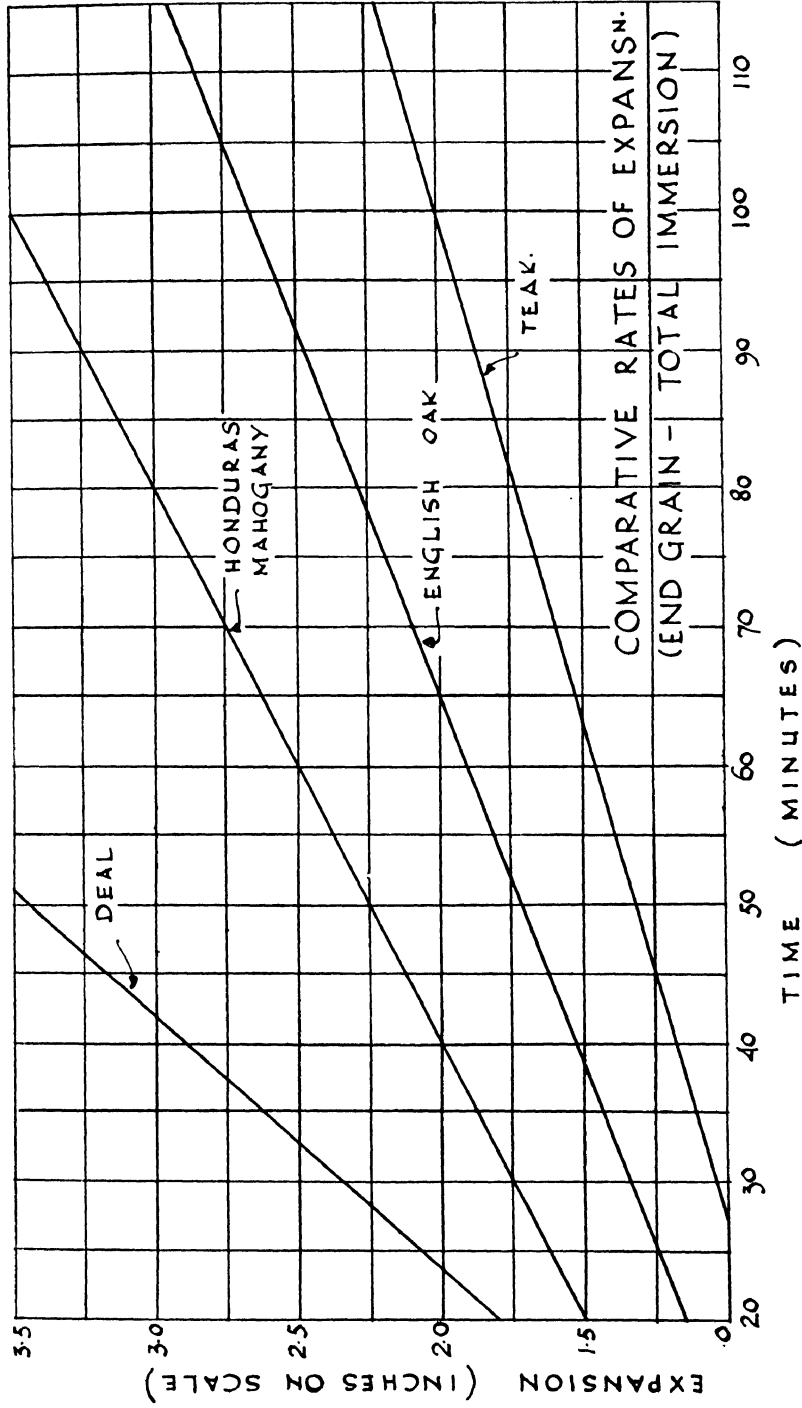


FIG. 69.—Graph showing Linear Expansion of Timbers due to Rise in Moisture Content.

## MORTARS AND CONCRETES

1. *Concrete Materials.*
2. *Voids in Divided Materials.*
3. *Proportioning and Mixing of Mortar and Concrete.*
4. *Non Load-bearing Concrete.*

## 1. CONCRETE MATERIALS.

A material which is composed of a large number of separate pieces is called a *discrete or divided* material. Examples are sand, gravel, cement, etc. The material may be finely divided like cement, plaster and sand, or coarsely divided like gravel, crushed granite, broken brick, etc.

Such grains or pieces may be united to form an aggregation or mass of "solid" material, and the force holding them together is called "adhesion" (compare with "cohesion" which is a force holding together atoms or molecules of the same substance—adhesion acts between the surfaces of adjacent grains or pieces). Some materials, for instance chalk or powdered clay, may be united by mere pressure—materials like gravel or broken stone or sand require an "adhesive," which is a separate substance introduced for this purpose, and which usually produces the desired effect by chemical action. In the case of cork-boards and some similar products the adhesive is glue, and this does not involve chemical action. Such a united material is called a *concrete* material, and when the constituents are sand, gravel, stone, etc. such as used in buildings, the resulting mass is called *concrete*. If sand alone is used, without the coarser stone, etc., we generally refer to the resulting material as *mortar*.

Mortar and concrete comprise the material to be united, called the *aggregate*, and the adhesive, called the *matrix*. In mortar the aggregate is sand (or occasionally finely-crushed waste stone); in concrete the aggregate is divided into "fine aggregate" (sand), and "coarse aggregate" (broken brick, stone, gravel, etc.). In both cases the matrix is hydraulic lime or, more usually, Portland cement. Plaster is of course a mortar, and the various gypsum products are cements, but we are considering here the structural materials, mortar and concrete, and when we refer to cement we mean one or other of the Portland cements.

In mortar and concrete the functions of the aggregate are:—

- (a) to act as fillers (they should therefore be "inert" materials),
- (b) to economise in matrix (which is the more expensive material),
- (c) to reduce shrinkage defects in the finished material (the matrices if used without aggregate are subject to appreciable setting shrinkage which usually produces cracks).

The function of the matrix is to bind together the particles of aggregate by combination with the water used for mixing. When the materials are mixed with water the mass is at first plastic and capable of being poured or cast into any shape, after a time, depending upon many factors, setting hard in that form.

## 2. VOIDS IN DIVIDED MATERIALS.

The shapes of the grains of a divided material are such that they do not pack closely together but have spaces or voids between. We have already seen the difference between the "bulk" volume and the "grain" volume of such a material. By a variation of the method of finding the grain volume we can determine the volume of voids in a given bulk volume. It is most conveniently expressed as a percentage of the bulk volume.

EXPERIMENT 43.—To determine the void percentage of a sample of sand.

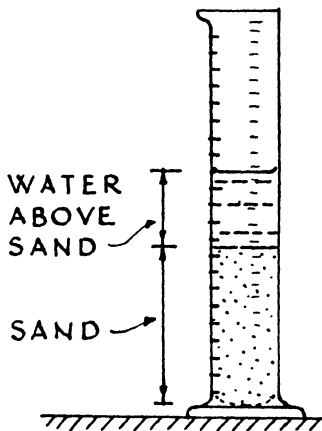


FIG. 70.—Finding Percentage of Voids in Sand.

For a fine material such as sand a glass graduated cylinder may be used, but for coarse aggregates a larger metal vessel is essential. Take as the sample of sand sufficient to about  $\frac{1}{4}$ -fill the cylinder and then introduce a known volume of water from another vessel. Stir with a thin rod to release air and consolidate the sand, leaving it with a level upper surface. Stirring should be only sufficient to get rid of all air and should not be done with a circular motion, otherwise the larger grains of sand will settle and the smaller ones collect at the top of the sample. Next find the volume of water standing *above* the sand, and deduct from the volume of water used, to give the volume of water occupying the voids.

Volume of water added to sand = 150 c.cm.

„ „ sand after consolidating = 82 c.cm.

„ „ water above sand = 118 c.cm.

Therefore „ „ „ in voids =  $150 - 118 = 32$  c.cm.

And volume of voids =  $\frac{32 \times 100}{82} = \underline{\underline{39 \text{ p.c.}}}$

For a given type of sand the experiment should be repeated several times, using different quantities of sand and water, and the average value taken. This is because the void volume varies with the positions taken up by the sand grains, and considerable variation may be noted.

**Grading of Aggregates.**—In the preparation of mortar and concrete it is best if the void percentage is as low as possible, for the fewer the voids the greater the density and strength. Some natural materials are found with grains all approximately of identical size; the void percentage in such cases may be as high as 50. Other materials are

composed of grains of varying sizes so that some of the finer particles fit into voids between the larger ones ; such a material has a low void percentage, possibly not more than 25, and is termed a *naturally graded* material.

If, as is often the case, a sand or gravel is not naturally graded it may be graded artificially. To do this we must first get to know the proportions of particles of various sizes which it contains, this is called *ungrading* and is carried out by means of sieves. Sieves are of shallow circular shape, having the bottom made of square-woven wire mesh, or in the very large sizes, of sheet steel perforated with square holes. The larger ones are called after the size of the mesh, thus :—2-in., 1½-in., 1-in., ¾-in., ½-in., ⅜-in., ¼-in., ⅛-in. Smaller ones are named according to the number of square holes per inch. Thus a "20" sieve has 20 holes per inch or 400 per square inch. The sieves from ⅛-in. upwards are intended to be used individually, but the "20" and smaller are arranged so as to fit into each other to form a nest, the nest being completed by a solid container as base and a solid lid with handle. A nest of standard sieves for sand is shown in Fig. 71 and comprises the following meshes :

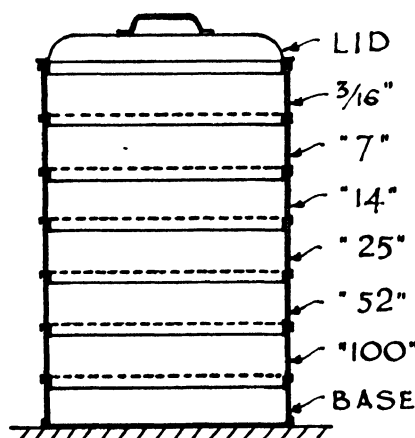


FIG. 71.—Standard Sieves for Sand.

⅜-in., No. 7, No. 14, No. 25, No. 52, No. 100. For ordinary laboratory purposes, however, standard sizes are not essential especially as they are altered from time to time in accordance with various regulations, and a nest comprising the following is suitable :—Nos. 20, 30, 40, 50.

In sieving, the material is placed on the mesh and the sieve agitated with either an alternating clockwise and anti-clockwise or forward and backward motion, keeping the sieve horizontal. It should never be shaken with an up and down motion or some of the material may be split, and in the case of a nest of sieves the finer grains will get between the sieves and make it difficult to separate them. All particles smaller than the mesh opening pass through, and all larger particles are retained on the mesh.

**EXPERIMENT 44.**—To ungrade a sample of sand.

Arrange the sieves in order, coarsest on top, fit the container on the base, and after weighing the sample, place it on the topmost sieve. Cover it with the lid and, grasping the whole in both hands

and holding them so that none will fall off, agitate them as described for at least 5 minutes. To save this labour machines are made for the purpose but one of these is unlikely to find a place in a Building laboratory. After thorough sieving empty out the contents of each sieve, and the base, and weigh them separately expressing the results as percentages of the weight of the whole sample.

Weight of sample of sand = 1,075 gm.  
Weight after ungrading :—

- |                                  |                           |
|----------------------------------|---------------------------|
| 1. Retained on "20" mesh         | 162 gm. = 15.07 per cent. |
| 2. Passing "20" retained on "30" | 392 gm. = 36.46 per cent. |
| 3. Passing "30" retained on "40" | 379 gm. = 35.26 per cent. |
| 4. Passing "40" retained on "50" | 77 gm. = 7.16 per cent.   |
| 5. Passing "50"                  | 65 gm. = 6.05 per cent.   |

Alternatively the separate grades may be measured by volume and expressed as percentages of the total volume *after sieving*. A method given in *Experimental Building Science*, by J. L. Manson, is of especial interest as showing the result of such a test in visual form and is useful if the specimens are to be kept for comparison with others. Instead of weighing or measuring the volume the sample is put first into a wide

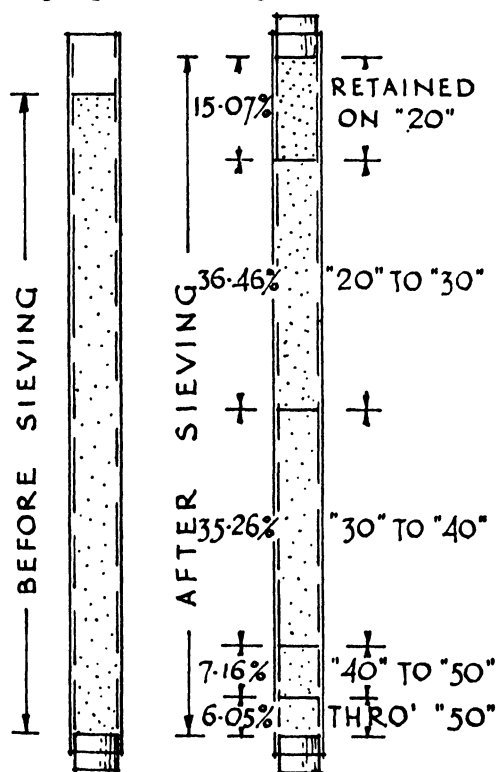


FIG. 72.—Ungrading a Sample of Sand.

glass tube some 18-in. long, corked at one end. The tube should not be filled completely as it will be found that the length of tube occupied by the separate grades after ungrading is greater than that occupied by the original sample. This, incidentally, shows clearly that a graded sand has fewer voids than when ungraded. The sample is then sieved and the various grades returned to the tube in order, the finest first and so on, each batch being separated by a paper disc from the last. The length of tube occupied by each grade is then measured, the percentage being that of the whole length occupied by the various grades after sieving.



**EFFECTS OF GRADING UPON VOID PERCENTAGE.**—After having ungraded the sand efforts should be made to lower the void percentage by artificial grading, *i.e.* by trial mixtures of the various grades. We cannot tell with any certainty whether a sand is well graded merely from the result of the ungrading test, the void percentage is the only sure criterion. The following experiment gives the results of ungrading and subsequently artificially grading a sample of silver sand.

**EXPERIMENT 45.**—To note the effects of artificial grading on a sample of sand.

A portion of the sample is first tested for void percentage.

Volume of water used = 150 c.cm.

„ „ sand = 64 c.cm.

„ „ water above sand = 127 c.cm.

$$\text{Therefore Void percentage} = \frac{23 \times 100}{64} = \underline{36 \text{ c.cm.}}$$

The remainder of the sand is then ungraded by sieving, the result being as in Experiment 44.

The next operation is to retain the coarser grains but to discard some of the intermediate and most of the very fine grains (most sands have too few coarse and too many fine particles). After repeated trials the following mixtures are recorded, together with their respective void percentages :—

- (a) Mixture composed of 45 gm. retained on " 20 "  
 79 gm. " 20 " to " 30 "  
 68 gm. " 30 " to " 40 "  
 11 gm. " 40 " to " 50 "  
 22 gm. passed " 50 "

Void percentage of mixture (a) = 33.3

- (b) Mixture composed of 45 gm. retained on " 20 "  
 45 gm. " 20 " to " 30 "  
 11 gm. " 30 " to " 40 "  
 11 gm. " 40 " to " 50 "  
 45 gm. passed " 50 "

Void percentage of mixture (b) = 25.5

Aggregates should be free from loam and clay, also organic matter such as vegetable fibres. Certain tests are standardized to ascertain, amongst other things, the presence or absence of organic substances and clay.

The test for organic matter is to take a specified volume of the aggregate and to add to it in a glass flask a specified volume of sodium hydroxide solution. The flask is then shaken up and left to stand for 24 hours, after which time the colour of the solution is compared with that of a standard colour solution prepared at the same time. The action of organic impurities upon the sodium hydroxide is to turn it from a colourless into a brown coloured liquid; if this colour is darker than the standard solution the impurities must be considered excessive. This test will be described in detail at a later stage.

The test for clay or silt is called the "Decantation test," a simplified version of which is as follows :—

**EXPERIMENT 46.**—To find the percentage of silt in a sample of building sand.

Place 100 c.cm. of the sand in a graduated cylinder, add water up to the 150 c.cm. mark, shake the cylinder well and then allow the sand to settle. After one hour the sand will be observed to have settled with a layer of fine silt above it, forming a distinct dividing line. Read off the volume of the sand and that of the silt. The silt should not exceed 6 per cent. of the total volume of the sand.

This small percentage, although undesirable, is permissible for it makes for ease of working during mixing and consolidating, and so might conceivably result in a stronger mortar or concrete than would be obtained without it. An excessive amount, however, is detrimental; the writer, in a series of tests on sands proposed for a reinforced concrete structure, found one type of sand with a proportion of 19 per cent. of clay, although it was very much below the average in organic matter, and was reasonably well graded.

### 3. PROPORTIONING AND MIXING OF MORTAR AND CONCRETE.

**MIXING SHRINKAGE.**—We have already noticed that a graded aggregate has a smaller bulk volume than the same aggregate ungraded. Similarly, when the dry materials for mortar and concrete are mixed, their combined volume is less than the total of their individual volumes. This can readily be shown by a simple experiment similar to the one described on page 93, but what is more important is the fact that, in making up the mortar or concrete water is used and, although the volume of this extra constituent is added to that of the sand, etc., the final volume of the wet mixture is still smaller than when the constituents are merely mixed in a dry state. The reason for this shrinkage is that the friction between the various particles is reduced by wetting them, so enabling them to produce a more compact mass.

**EXPERIMENT 47.**—To show the shrinkage of concrete after mixing.

For the purpose of the experiment a fairly fine "coarse" aggregate should be used, say granite chips not larger than  $\frac{3}{8}$ -in. graded down but with dust and particles smaller than  $\frac{1}{8}$ -in. removed. The fine aggregate should be clean, graded sand, and the matrix Portland cement. The question of proportioning the materials is gone into later but suppose that we have decided upon proportions of 1 of cement, 2 of sand, and 4 of coarse aggregate (by volume); this is a very commonly used mix.

Take a steel tube, closed at one end by a screwed plug or cap, or by welding on a disc,  $1\frac{1}{2}$ -in. or 2-in. in diameter and with an internal length of 1-ft. 9-in. Divide the length into three parts, 3-in., 6-in., and 12-in. respectively as shown in Fig. 73. Place the granite chips in the tube so that they reach the

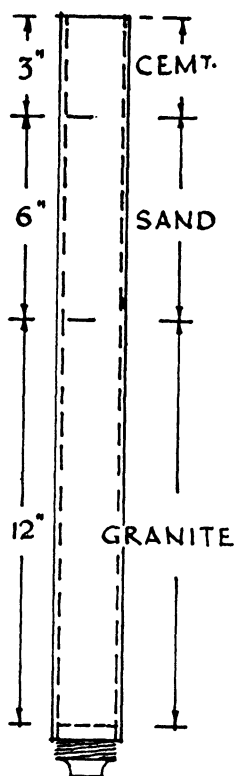


FIG. 73.  
To Show Shrinkage of  
Concrete after Mixing.

lower mark after tapping the side of the tube to consolidate them. Then place a paper disc on top and put in sufficient sand to rise to the next mark (again after consolidating). Place a further disc on the sand and fill the tube to the top with cement. We now have the materials in the tube in the proportions 1 : 2 : 4 by volume.

Now empty out the materials on to a glass-topped mixing table, remove the paper discs, and with a gauging trowel mix the materials thoroughly in a dry state. When they appear to be well mixed as shown by a uniform appearance and colour start to add water slowly, mixing all the time until the concrete is of such consistency that water does not flow from it. Now place the mixture back into the tube, tap the side to consolidate the concrete, and ascertain the length of tube it occupies by measuring the distance from the top of the mixture to the rim of the tube and subtracting from the total internal length.

Actual experimental results are :—

Length occupied by separate materials dry = 21-in.

„ „ „ mixed concrete = 15-in.

Therefore Shrinkage =  $21 - 15 = 6\text{-in.} = \frac{6 \times 100}{21}$   
= 28.6 per cent.

In practice the shrinkage may be from 20 per cent. to 33 per cent. and, for given materials, must be known in order to ascertain the quantities of dry materials necessary to produce a given volume of finished concrete.

**QUANTITIES OF MATERIALS.**—For any given proportions of materials and for a known percentage shrinkage we can therefore calculate the quantities of materials required. Let us suppose the materials and mix used in Experiment 47 to be proposed for laying an area of paving, 10-ft.  $\times$  27-ft.  $\times$  6-in. thick. The volume of finished concrete is thus 135 c.ft. or 5 c.yds. Each c.yd. of the concrete has a volume equivalent to  $\frac{100 - 28.6}{100}$  or  $\frac{71.4}{100}$  of the combined volume of dry materials, therefore

to produce a volume of 1 c.yd. of finished concrete  $\frac{100}{71.4}$  or 1.4 c.yds. of dry materials will be required. This is equivalent to  $1.4 \times 27 = 37.8$  c.ft. and according to the proportions 1 : 2 : 4 the

volume of cement required =  $37.8 \div 7 = 5.4$  c.ft.

volume of sand required =  $5.4 \times 2 = 10.8$  c.ft.

and volume of granite required =  $5.4 \times 4 = 21.6$  c.ft.

Although the volume of cement required is 5.4 c.ft. this may represent a weight of cement varying according to the manner of measuring the volume. The cement may be measured loosely in a container or it may be consolidated by vibration. To overcome this difficulty cement is measured by weight and the volume reckoned at the rate of 1 c.ft. for each 90-lb. The weight of cement required per c.yd. of finished concrete in the present case is therefore  $90 \times 5.4 = 486$ -lb., so that for 5 c.yds. the weight will be 2,430-lb., and as cement for use in this country is supplied in 1-cwt. bags 22 bags would be required for the job.

PROPORTIONS OF MATERIALS.—In Experiment 47 we adopted the proportions 1 : 2 : 4 quite arbitrarily. Actually it is extremely unlikely that, for the materials we used, these proportions were ideal. In order to produce the densest concrete it must have as few voids as possible, and there are several ways of proportioning the materials to achieve this result.

In one method the sand and coarse aggregate are mixed in various proportions, each mixture being tested for void percentage. The mixture with the *fewest* voids is selected and sufficient cement-water mixture added to fill the voids.

By another method approximate proportions are assumed and a sample of concrete prepared and tested for shrinkage as in Experiment 47. The same weight of cement is taken and the same combined weight of sand and granite but with their proportions varied. Further samples are made up in this way and the one which shows the *greatest* shrinkage will be the densest concrete.

Both of these methods have the merit of being empirical, *i.e.* the proportions are decided as a result of experiment. There are also various theoretical methods which aim at filling the aggregate voids with sand and the whole of the resulting voids with cement. In these cases, however, the effect of the mixing water is ignored, or only estimated, and it has been proved that the strength of the concrete depends as much, within limits, on the amount of water used as upon the proportions or grading of the aggregate. Such methods are deferred until a later volume.

EFFECT OF MIXING WATER UPON STRENGTH.—It is not always realised that excessive voids in the finished concrete may be due to the use of too much water in the mixing. There is not much point in going to a lot of trouble in the grading of the aggregates, and their proportioning, if voids are allowed to occur in this way. Of the water added to the materials a certain amount is necessary for the chemical action of setting. The remainder, apart from assisting consolidation by lubrication and so giving "workability," serves no useful purpose and, on evaporating from the finished work, leaves voids, no matter how well graded and proportioned

the materials. The minimum amount necessary is surprisingly small, only a fraction of the amount used as a matter of course by many experienced persons, but the use of this minimum amount results in a very "dry," unworkable mix. This difficulty may, however, be minimised by suitable tamping or vibrating of the newly mixed concrete.

In the cast stone industry, so as to release moulds for re-use as frequently as possible, the concrete used is so "dry" as scarcely to wet the hands when it is taken up and squeezed. But after filling the moulds the mix is tamped with pneumatic or electric rammers and in a few moments begins to "flow" or become plastic, rather like moist clay. This is the ideal consistency for maximum strength and provided curing is properly done the finished product will be most satisfactory. Curing is the term used to denote the procedure of protecting the concrete from evaporating of its moisture during early life—until setting is more or less complete. If such concrete is merely left with no protection it may dry excessively and so be seriously weakened.

A series of experiments may usefully be carried out to show how, other factors being equal, the quantity of water used affects the strength of the concrete. Particulars of such tests are given below:—

EXPERIMENT 48.—To show variation of strength with consistency.

For convenience and speed mortars were tested instead of concretes, the specimens being 2-in. cubes tested in compression to find their crushing strength. An artificially graded sand was used, having a determined void percentage of 20·4 and the proportions used were 1 of cement to 4 of sand. Three specimens of each mix were made and, although the number of steel moulds available was limited and the specimens therefore made on different dates, all were cured under identical conditions (in moist air for 24 hours and subsequently out of the moulds and under water) and tested at the same age.

For specimens A 8 per cent. of water was used.

"	"	B	10	"	"	"	"	"	"
"	"	C	12	"	"	"	"	"	"
"	"	D	14	"	"	"	"	"	"
"	"	E	16	"	"	"	"	"	"
"	"	F	18	"	"	"	"	"	"

The cubes were removed from the water after 14 days and allowed to drain for 1 hour before testing.

The crushing strengths were:—

Specimen	A	..	..	1·52 tons	Av.
"	B	..	..	1·31	" "
"	C	..	..	1·14	" "
"	D	..	..	·94	" "
"	E	..	..	·76	" "
"	F	..	..	·61	" "

These results are shown graphically in Fig. 74.

The proportions of water used in this experiment were percentages by weight of the dry materials, chosen from empirical considerations. In the laboratory the materials can easily be stored in a dry state, but the same cannot be said of the materials on a job. Especial care is normally taken with cement by storing it in a dry place, for obvious reasons, but it is not practicable to keep sand and coarse aggregate in a dry state even if it were possible to bring them to the site in such a state. There are thus certain difficulties attending the preparation of concrete on the job which are absent in laboratory work.

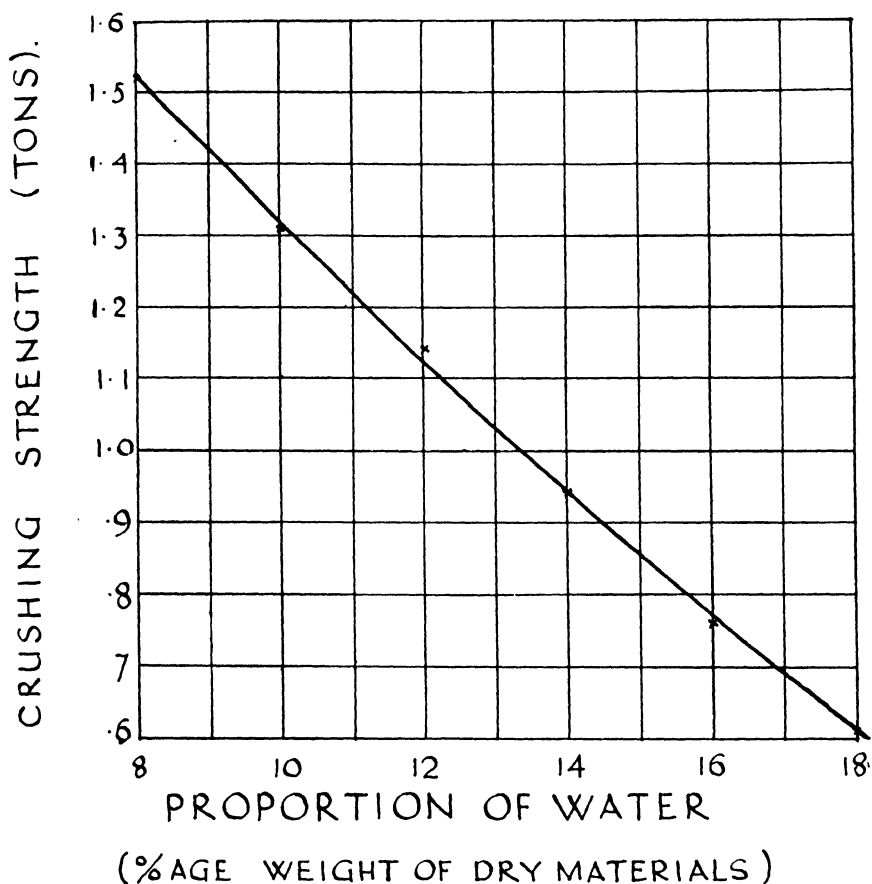


FIG. 74.—Variation of Strength with Porosity caused by Excess of Mixing Water.

Coarse aggregates like broken brick or stone may be porous and thus liable to absorb some of the mixing water. The effect of this would be to reduce the workability of the mix, and its effect must be taken into account when deciding the proportion of water to use. In such cases the porosity percentage of the aggregate must be found, either by the method

given in Experiment 36, page 61, or more usually by determining the percentage (of the dry weight) of water absorbed after 24 hours' immersion. (See Experiment 37, page 63.)

Apart from the porosity or otherwise of the aggregate it will never be dry upon delivery and will be unlikely to be dry when required for use. The percentage of water associated with it as "wetness" must therefore be determined, for this will reduce the amount of mixing water to be added. This may be done by weighing a sample of the wet aggregate, drying it and re-weighing, but as a rule a more accurate method, based upon the consistency of samples of mixed concrete, is used in practice. This is left over to the Chapter on Concrete in a subsequent volume.

The really important point about wet aggregate is that its bulk volume varies with the degree of wetness, increasing by anything up to one-third with comparatively small amounts of water. This phenomenon is termed "bulking," and the amount of bulking must be determined for all important concrete work. It is more apparent in the case of sand than coarse aggregate because of the comparatively small size of the grains, but this also is a problem that cannot be considered further at this stage.

#### **4. NON LOAD-BEARING CONCRETE.**

Certain items of construction, often carried out in concrete, are not called upon to carry loads. They include internal partitions, filling over vaulting or structural floors to give a level surface to receive roof or floor finishes, internal walls or other construction designed to give insulation against heat or sound, and external panels of wall in buildings of skeleton construction. Except in the last-named instance, in which weather and wind pressure are to be withstood, the construction should be as light and porous as is consistent with questions of stability and handling. Materials normally used for such work are clay, cork composition, plaster, wood-fibre, asbestos, and special concretes. It is the last-named that will be touched upon now.

Perhaps the most obvious means of securing low density is by the use of highly porous aggregate with just sufficient cement to bind it together without filling the voids to any great extent. Such aggregates include pumice, coke-breeze, slag and clinker. Pumice is a volcanic material, exceedingly porous on account of its origin yet reasonably strong, and when free from ash and other dust is one of the best materials. It is not found in this country and is therefore rather expensive. Coke-breeze comprises the finer grades of gasworks coke, and if entirely free from unburnt coal, etc. is suitable for the purpose. It is obtainable in all industrial districts and is perhaps the most popular of these materials.

The slag used is blast-furnace slag granulated or "foamed" by quenching whilst still hot. Clinker comprises the fused ash, etc. from coal-fired furnaces. The chief point to guard against when using these aggregates is the excessive moisture movement of the concretes made with them; this can be limited to a certain extent by proper treatment between mixing and setting. They are also likely to contain some small proportion of sulphur compounds which attack any embedded steel, but for plain (non-reinforced) concrete their adverse effect is not serious.

In recent years many efforts have been made to produce highly porous concrete, more especially for insulation purposes. One method, which has been attended with some success, is to include broken ice in the aggregate. This melts out after slight early strength has been attained and leaves a highly honeycombed structure very suitable for such a purpose. Another method involves the use, in mixing, of chemicals which produce a frothing action by the release of carbon dioxide or other gases—somewhat on the lines of the effect of baking powder in cookery. Such concretes are referred to as "aerated" or "cellular" concretes, but again the moisture movement is appreciable and must be borne in mind in the construction.



## CHAPTER VI

### CHEMICAL ACTION

1. *Physical Change and Chemical Change.*
2. *Elements, Compounds and Mixtures.*
3. *Chemical Symbols, Formulæ and Equations.*

#### 1. PHYSICAL CHANGE AND CHEMICAL CHANGE.

We have already seen that, by altering conditions of temperature and pressure, we can have water in any of the three states—solid, liquid and vapour. These changes are *physical* changes, since all three are merely different forms of the same substance, water. Physical changes are reversible ; for instance if water is turned into ice by a reduction in temperature it can be re-converted into water by again raising its temperature. If it is turned into steam it can with equal ease be turned back into water.

If we put a few chips of dry wood into a test tube and heat it strongly the wood turns brown and grey fumes are given off. Some of these condense as a brown liquid on the sides of the test tube (it can all be so condensed if we wish) and after a time the production of fumes ceases and a black, dry residue is left at the bottom ; this is charcoal or carbon. We have changed the wood into carbon and the brown liquid, caramel, but we cannot hope to re-convert these into wood. This is an example of a *chemical* change, and the majority of chemical changes are not reversible.

In the case of the water undergoing physical change the molecules remain molecules of water throughout ; their composition or arrangement of atoms remains unchanged. But in the case of the wood the atoms have re-grouped themselves to form substances differing from the original wood.

INDICATIONS OF CHEMICAL ACTION.—Chemical changes are usually effected by the application of heat, as in the last case, by electricity, by the interaction of different substances on contact, sometimes by the action of light, or by some combination of these.

Chemical action is invariably accompanied by a change of temperature and an apparent change in the weights of the substances involved.

#### 2. ELEMENTS, COMPOUNDS AND MIXTURES.

In Chapter I we distinguished between elementary and compound substances. An elementary substance or *element* is one composed entirely of atoms of one kind ; it cannot therefore be chemically divided into any simpler substances, but it can combine chemically with other substances to form new and more complex substances.

Such a substance, produced by the interaction of other substances, is obviously not composed of one kind of atom only ; its various atoms are combined to form molecules and it is called a *compound*.

Most of the building materials are *mixtures*, either of elements or compounds or of both. Indeed, most natural substances are very complicated mixtures ; when we heat the wood in a test tube we separate it into carbon (an element) and caramel, the caramel itself being still a mixture of many compounds consisting of various combinations of carbon, oxygen, sulphur, nitrogen and other elements.

ELEMENTS.—So far as is known there are 93 elements. Of these only 20 or so are of common occurrence, the remainder being extremely rare and, from our viewpoint, unimportant. Some do not exist in a free state in nature, but are combined in various compounds and mixtures.

As will be seen from Table 5, most of the elements are metals. These have certain characteristics in common. They are dense and opaque, they readily conduct heat and electricity, and they have a typical sheen or lustre. All except mercury are normally solids. The non-metals are in most cases gases ; carbon and sulphur are important exceptions.

TABLE 5.  
TABLE OF THE COMMONER ELEMENTS.

<i>Element</i>	<i>Symbol</i>	<i>Nature</i>	<i>Normal state</i>	<i>Atomic weight (approx.)</i>
Aluminium .. ..	Al	Metal ..	Solid ..	27
Calcium .. ..	Ca	" ..	" ..	40
Carbon .. ..	C	Non-metal ..	" ..	12
Chlorine .. ..	Cl	" ..	Gas ..	35.5
Copper (Cuprum) .. ..	Cu	Metal ..	Solid ..	63.5
Hydrogen .. ..	H	Non-metal ..	Gas ..	1
Iron (Ferrum) .. ..	Fe	Metal ..	Solid ..	56
Lead (Plumbum) .. ..	Pb	" ..	" ..	207
Magnesium .. ..	Mg	" ..	" ..	24
Mercury (Hydrargyrum) .. ..	Hg	" ..	Liquid ..	200
Nitrogen .. ..	N	Non-metal ..	Gas ..	14
Oxygen .. ..	O	" ..	" ..	16
Phosphorus .. ..	P	" ..	Solid ..	31
Potassium (Kalium) .. ..	K	Metal ..	" ..	39
Sodium (Natrium) .. ..	Na	" ..	" ..	23
Sulphur .. ..	S	Non-metal ..	" ..	32
Tin (Stannum) .. ..	Sn	Metal ..	" ..	119
Zinc .. ..	Zn	" ..	" ..	65.5

Although the elements are each composed of one kind of atom only, they are normally made up of molecules each consisting of several atoms.

Atoms do not normally exist in a free state ; the molecule is the smallest particle of matter, element or compound, which can do so.

COMPOUNDS.—A compound is always made up of the same elements in the same proportions, irrespective of the process by which it is formed. Its properties may be very different from those of its constituents, and it cannot be separated into its original elements other than by chemical or electrolytic action.

Common examples of compounds are :—

Water ..	..	composed	of Hydrogen and oxygen.
Chalk ..	..	„	„ Calcium, carbon and oxygen.
Common salt ..	..	„	„ Sodium and chlorine.
Quicklime ..	..	„	„ Calcium and oxygen.
Red lead ..	..	„	„ Lead and oxygen.

MIXTURES.—A mixture differs from a compound in several important respects. Its constituents may be present in any desired proportions ; it is usually possible to discern in the mixture particles of the individual constituents ; their properties are not affected by being mixed ; they may be separated again by means other than chemical action.

Common examples of mixtures are :—

Air ..	..	composed	of Nitrogen and oxygen—a mixture of elements.
Oil putty ..	..	„	„ Whiting and oil—a mixture of compounds.

EXPERIMENT 49.—To show the difference between a compound and a mixture.

Take a small quantity of flowers of sulphur and about twice the weight of iron filings. Both are examples of elements. Mix the two ingredients thoroughly in a mortar, then separate into two portions, and lay one of these aside. Scrutinize one portion carefully, if necessary under a magnifier, and separate particles of iron and sulphur may be discerned. This is a *mixture*, intermediate in colour and appearance between iron filings and flowers of sulphur. Each of the constituents has retained all of its properties ; if the mixture is exposed to moist air the iron will rust ; if it is heated gently the sulphur will melt ; if it is laid on a sheet of paper and a magnet drawn across underneath the iron can be separated from the sulphur ; if it is placed in water and stirred with a circular motion the iron, being denser, will settle to the bottom first, to be followed by the sulphur—two distinct layers ; if it is placed in a test tube, well covered with carbon disulphide (a highly inflammable liquid) and shaken, the sulphur will dissolve and disappear, leaving only the iron visible.

Next take the second portion, place it in a test tube and, using a test tube holder, introduce it into a bunsen flame, gradually at first so as not to crack the tube. Soon the contents begin to glow ; at this point remove the tube from the flame and observe that the

mixture continues to glow brightly and emit fumes. When this obvious chemical action has ceased, allow the tube to cool and then remove and examine the contents, a hard yet porous looking substance of a dark grey colour. Pulverize it in the mortar and examine it afresh ; it is now a dark grey powder and none of the tests applied to the first portion produces any result. It is a *compound*, iron sulphide, and to verify this the sulphide test may be carried out. Simply pour on to it some dilute hydrochloric acid and be prepared for one of the traditional chemistry " stinks " ; the gas given off is hydrogen sulphide, sulphuretted hydrogen or " rotten egg gas."

### 3. CHEMICAL SYMBOLS, FORMULÆ AND EQUATIONS.

**SYMBOLS.**—Everyone knows the convenience of symbols in mathematics. Similarly in recording chemical action symbols are used, not only as a labour and time saving device, but for clearness. Incidentally the use of chemical symbols enables us to see at a glance the quantitative relationship between the substances involved in a chemical change.

The symbol used for an element is in most cases the initial letter of its name ; thus carbon is represented by the capital letter C. If, however, two or more elements have names beginning with the same letter, one further letter of the name is added as a " small " letter, for instance Ca for calcium, Cl for chlorine, etc. The symbol for any element is thus easy to remember if we bear in mind that in some cases it is the Latin name from which the letters are taken. Table 5 gives the symbols of the commoner elements.

When we write Zn we mean not merely zinc but one atom of zinc, O means one atom of oxygen, etc.

**FORMULÆ.**—To represent two or more atoms combined in a molecule of an element we place a small subscript figure after the symbol. For instance  $O_2$  represents one molecule of oxygen which contains two atoms of oxygen.  $O_3$  represents one molecule of ozone, an unstable form of oxygen, which has three oxygen atoms.

The molecule of a compound is similarly represented by the symbols of its constituent elements. Thus CaO means one molecule of calcium oxide, composed of one atom of calcium and one atom of oxygen.  $CaCO_3$  represents one molecule of calcium carbonate, NaCl sodium chloride, etc. (Note that although in algebra we infer the multiplication sign when two quantities are placed side by side, in chemical formulæ this is not the case. We cannot multiply sodium by chlorine or hydrogen by oxygen.)

If we wish to represent more than one *molecule* we prefix its formula by a large figure.  $2CO$  means two molecules of CO (carbon monoxide)—compare this with  $CO_2$  which means one molecule of carbon dioxide ( $CO_2$ ).

Sometimes it is convenient to simplify a formula by the use of brackets. These are used as in algebra, and a small subscript figure

after the brackets indicates that all within the brackets is multiplied. An example will make it clear ; thus— $\text{Ca}(\text{OH})_2$  is the usual way of putting  $\text{CaO}_2\text{H}_2$  which is one molecule of calcium hydroxide or slaked lime.

One more important point about formulæ. We may see on the laboratory shelves a label  $\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$ . Here we have a stop between two of the quantities, the second quantity usually being a number of molecules of  $\text{H}_2\text{O}$ . We may see another label merely  $\text{Na}_2\text{CO}_3$  ; this is a white powder, sodium carbonate in a dry form. The first jar contains large, whitish, transparent crystals, sodium carbonate in its more usual crystalline form. As explained in Chapter I both substances are chemically identical, but the crystalline form contains water of crystallization without which the crystals could not form. Although the 10 molecules of water are in close association with the 1 molecule of sodium carbonate, they are not held strongly enough to combine chemically, and are dispersed by slight heating so that the "dry" form of sodium carbonate is left. There are many substances similar in this respect, for instance copper sulphate, magnesium sulphate, etc.

EQUATIONS.—If we represent various substances by their chemical formulæ we can record any chemical action simply and quickly in the form of an equation. Thus if we put down :— $2\text{H}_2 + \text{O}_2 = 2\text{H}_2\text{O}$  we mean that 2 molecules of hydrogen combined chemically with 1 molecule of oxygen yield 2 molecules of water.

Note that both sides of the equation must balance ; each atom represented on one side must appear also on the other side. Note also that the above equation is only possible because the chemical action which it represents is possible ; we could not put down :— $\text{Pb} + \text{Sn} = \text{PbSn}$  because, although both sides balance and although we *mix* lead and tin to make solder, the equation does not represent a possible *chemical* change.

In stating :— $2\text{H}_2 + \text{O}_2 = 2\text{H}_2\text{O}$  we have, so to speak, added two quantities, and this represents the interaction of two substances to form a third. This process is called *synthesis*, just another word for "formation."

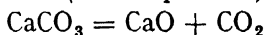
If we wish to express the chemical action of removing the oxygen from water and leaving hydrogen (this is of course possible) we might put down as in algebra :— $2\text{H}_2\text{O} - \text{O}_2 = 2\text{H}_2$ . This, however, is not usual and such a chemical change, called *analysis* and meaning "decomposition," is expressed :— $2\text{H}_2\text{O} = 2\text{H}_2 + \text{O}_2$ .

CHEMICAL CALCULATIONS.—The final column of Table 5 gives the *atomic weights* of the elements, and the student will doubtless have inferred, from the absence of units, that these are *relative* weights. The actual weight of a single atom is clearly impossible of statement in the ordinary way, but by reference to a standard (as in specific gravity) the weights of

single atoms of different elements may be compared. The standard is Hydrogen, the lightest element, and as its atomic weight is taken as unity those of the remaining elements are all whole numbers.

By the use of atomic weights it is possible to express, in terms of weight, the proportions of any chemical compound. Thus in calcium oxide (quicklime) we have a total molecular weight of 40 (Ca) + 16 (O) = 56, and although the molecule comprises only one atom of each element the proportions by weight are calcium 40/56 and oxygen 16/56. Similarly water (H<sub>2</sub>O) comprises hydrogen 2/18 and oxygen 16/18 by weight. The proportions may of course be represented in any units ; for instance 1-cwt. of pure quicklime must contain exactly 80-lb. of calcium and 32-lb. of oxygen—9 gallons of pure water (weighing 90-lb.) must contain exactly 10-lb. of hydrogen and 80-lb. of oxygen—etc., etc.

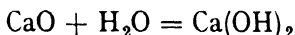
We are thus able to calculate with certainty the weights of all substances taking part in a chemical change. In the "burning" of limestone to produce quicklime (see Chapter XI) the equation is :—



Substituting the atomic weights we get :—

$$\begin{array}{rcl} 40 + 12 + 3(16) & = & (40 + 16) + (12 + 2(16)) \\ \text{or} \quad 100 & = & 56 + 44 \end{array}$$

(Notice that both sides of the equation balance, both as to the atoms concerned and the totals of atomic weights : this incidentally demonstrates the Law of the Indestructibility of Matter). This equation shows that from every 100 parts of calcium carbonate 56 parts of calcium oxide are obtained, the 44 parts of carbon dioxide being allowed to escape into the air. Thus, as before, 100-lb. of calcium carbonate would yield 56-lb. of quicklime. Similarly, when the quicklime is slaked with water the action is :—



Assuming that no more nor less than the correct amount of water is used, the figures are :—

$$\begin{array}{rcl} \text{CaO} + \text{H}_2\text{O} & = & \text{Ca(OH)}_2 \\ (40 + 16) + (2 + 16) & = & 40 + (16 + 16) \\ 56 + 18 & = & 74 \end{array}$$

Thus to each cwt. of quicklime 36-lb. of water must be added, the weight of slaked lime produced being 148-lb.

## CHAPTER VII

### AIR

1. *Oxidation and Reduction.*
2. *Oxygen.*
3. *Nitrogen.*
4. *Combustion.*

#### 1. OXIDATION AND REDUCTION.

It is well known that without air no life would be possible on the earth, because it is necessary for respiration and also because the constant evaporation and condensation of water has been necessary throughout the ages, and is still necessary, to make the earth's crust suitable to sustain life. It is therefore convenient to commence the study of chemical action by considering the significance of air and its effects upon different substances under various conditions.

##### Oxidation.

EXPERIMENT 50.—To observe the effect of heating metal in air.

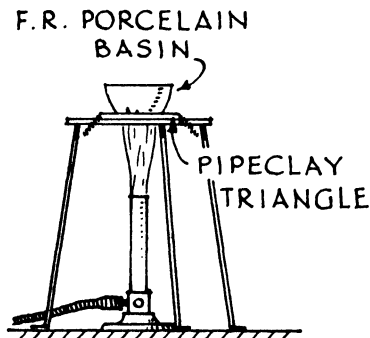


FIG. 75.—Formation of Oxide on Metals.

Scrape a thin piece of iron perfectly clean and bright, and heat it in a small porcelain basin over a Bunsen flame as in Fig. 75 for ten minutes or so. Then allow it to cool and examine it. It will be seen to be coated with a thin peel or scale, bluish-black in colour.

Repeat the experiment with clean copper foil, and the copper will be found to be covered with a black scale which can be peeled off.

Evidently chemical action has taken place, for the scale is in both cases very dissimilar in appearance to the original metal. Remembering

that chemical action is accompanied by an apparent change of weight of the substances involved, let us see whether such is the case in the present instance.

EXPERIMENT 51.—To note the change in weight of metal heated in air.

Repeat the experiments with iron, copper and also a piece of bright sheet lead, weighing the basin and contents both before heating and after cooling. The iron and copper produce a scale as before, but the lead becomes coated with a yellow powder. A slight difference in weight is discovered in all three cases, not a

decrease as might be assumed, but an increase. Here are experimental figures :—

Weight of basin and iron before heating	=	25·811 gm.
" " " " " after cooling	=	26·597 "
Increase in weight of iron	=	·786 "
Weight of basin and copper before heating	=	10·931 "
" " " " " after cooling	=	10·96 "
Increase in weight of copper	=	·029 "
Weight of basin and lead before heating	=	52·92 "
" " " " " after cooling	=	53·064 "
Increase in weight of lead	=	·144 "

The scales on the pieces of metal may remind us of the behaviour of these metals when exposed to a moist atmosphere. Iron becomes coated with a layer of rust which we may have observed to attain great thickness, sometimes sufficient to come away in fairly large sheets so that scarcely any metal is left. Copper quickly goes black and receives in the course of time a bright green coating, and the surface of sheet lead turns dull and grey in colour. Are these coatings due to chemical action ? In the case of iron it is easy to find out.

**EXPERIMENT 52.**—To note the effect of rusting upon iron.

Weigh an evaporating dish containing some clean iron filings (if they are oily shake them up in ether, pour this off, and allow them to dry). Pour a few drops of water on to them, "swish" them around the sides of the dish so as to present a large surface, and dry them in a water oven. Repeat the moistening and drying several times, or alternatively moisten them and put them away in a safe place for a week. When the filings are rusty and dry weigh the dish again.

Experimental figures are :—

Weight of dish and filings before rusting	=	61·48 gm.
" " " " " after rusting	=	62·451 "
Increase in weight of iron	=	·961 "

This result should be compared with the result of Experiment 51 (the iron) both expressed as percentages. The two results are different because the substances are different.

In all these cases the increase in weight can only have come from the air. We have therefore either used up some of the air in the chemical action, or something from the air ; either of these may be possible for we know that air is matter and has weight. To prove that the increase has come in some way from the air we must carry out a similar experiment in an enclosed volume of air.

**EXPERIMENT 53.**—To observe the effect of rusting of iron in an enclosed air space.

Take a large test tube, wet the inside and put in clean iron filings so that they adhere to the sides. Invert the tube as shown in



Fig. 76, supporting it so that the mouth is below water level in a beaker, mark the water level in the tube, and leave it for a week. It will then be observed that the iron has rusted and the water level inside the tube has risen. Pour more water into the beaker

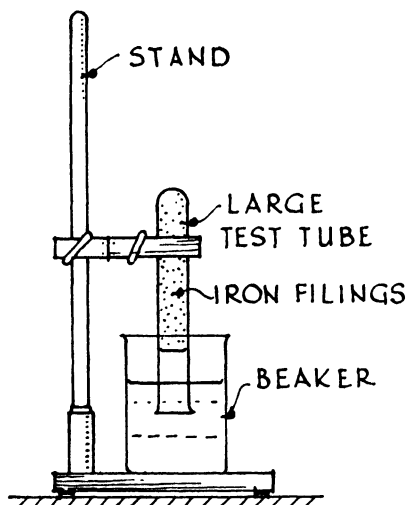


FIG. 76.—Effect of Oxidation upon the Enclosing Air.

until both levels coincide and again mark the level on the side of the tube. Then, placing the thumb over the mouth of the tube, turn it upwards and, at the moment of removing the thumb, introduce a flame from a wood splint. The flame is extinguished immediately, showing that the tube does not contain air but a gas which does not support combustion.

Now pour water into the tube up to one of the marks, pour out into a graduated cylinder and measure its volume. Next fill the tube up to the other mark and measure the volume similarly. The greater volume is the volume of air in the tube at the start of the experiment, and the difference between the two volumes is the amount the water rose in the tube. The latter is found to be about one-fifth of the former, indicating that about one-fifth of the air in the tube disappeared.

**EXPERIMENT 54.**—To observe the effect of respiration in an enclosed air space.

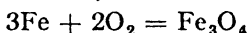
Place two or three peas in a test tube with just sufficient water to cover them. Seal the tube with a tightly-fitting rubber bung and leave for a week, after which time the peas will be seen to have sprouted. Now hold the tube in an inverted position with its mouth under the surface of a dilute solution of sodium hydroxide. This will slowly rise into the tube to the same level as did the water in the last experiment, showing that the peas have used up the same proportion of air as the iron did.

From these two experiments we learn that rusting and respiration use up a part of the air amounting to about one-fifth of its volume. We shall see later that the burning of a substance has exactly the same effect.

**COMPOSITION OF AIR.**—We can conclude from this that air consists of two parts, one of which is removed by heated metals, rusting iron, by respiration and by burning. This part, amounting to one-fifth, is called the *active* constituent and the remainder is called the *inactive* constituent. The two are thus present in air in the proportion of about 1 to 4. The active constituent is the gas *oxygen* and the inactive constituent another gas *nitrogen*. (In atmospheric air traces of other gases are present along with the nitrogen ; the atmosphere is therefore not pure air.)

**OXIDES.**—We recognise oxygen as one of the elements given in the table on page 103, its symbol being O. Oxygen combines readily with many other elements to form compounds called *oxides*. *An oxide is a compound of one element with oxygen, not merely a compound containing oxygen.*

Let us now see more clearly what happened in the foregoing experiments. In Experiments 50 and 51 the iron, under the action of heat, combined with the oxygen of the air to form iron oxide. The amount of oxygen which combines with another substance depends upon the conditions of the experiment, and sometimes this is so with the same substance. There are, for instance, three different oxides of iron. In the present case 4 atoms of oxygen combined with every 3 atoms of iron to produce 1 molecule of "tri-ferric tetroxide," thus:—



This particular oxide of iron is frequently called magnetic oxide. Other oxides are ferrous oxide ( $\text{FeO}$ ) and ferric oxide ( $\text{Fe}_2\text{O}_3$ ); the latter is used as a pigment in paints under the name of Venetian Red, and also as a fine polishing powder under the name of Jewellers' rouge. It is prepared by strongly heating ferrous sulphate ( $\text{FeSO}_4$ ) or by extracting it from "hæmatite" ore by smelting, as explained later. In Experiment 52 1 atom of oxygen combined with each atom of iron in the presence of moisture to form hydrated ferric oxide ( $\text{Fe}(\text{OH})_3$ ).

To return to Experiment 51, the copper also combined with oxygen to form an oxide of copper, and the lead to form oxide of lead. Lead is another element which forms more than one type of oxide. The yellow powder produced in the experiment is lead monoxide ( $\text{PbO}$ ). If this is heated in air at a high temperature it takes up further oxygen to form "tri-plumbic tetroxide" ( $\text{Pb}_3\text{O}_4$ ); this is commonly called "red lead" and is used in conjunction with linseed oil for jointing iron pipes. It is also used in oil paint as a base, also as a drier on account of its high proportion of oxygen which is necessary for the "drying" of the paint. "White lead," also used as a base in paint, is not an oxide but lead carbonate ( $\text{PbCO}_3$ ).

Of all the elements only about a dozen do not form oxides, and these include the precious metals gold, silver and platinum.

The rusting of iron and structural steel (which is iron containing a small percentage of carbon) presents a serious difficulty, for as we have mentioned the rusting or oxidation is continuous. The scale not only does not adhere to the metal but is porous, and oxygen thus has access to the surface of the metal until the whole of it is rusted away. These metals therefore always need to be protected from the action of oxygen by painting or otherwise.

The oxides of copper, lead and zinc, do adhere to the metal and thus in themselves form a protective coating. The oxide of zinc, however, is not sufficient protection against some acids, and this accounts for its inferior durability as a building material as compared to copper and lead.

Tin is not affected by atmospheric moisture but its high cost limits its use to "tinning" other metals such as sheet steel, etc. Tin containers or "tins" are, of course, merely tinned steel, and when the coating becomes damaged and the steel exposed rusting occurs.

We shall see later that burning or combustion is merely a rapid oxidation, and that the "drying" of oil paint is also a chemical process involving oxidation, as also is the production of oilskin cloth, linoleum, etc.

Oxygen combines not only with metals to form oxides but with some non-metals too, especially carbon and sulphur. These oxides are of great importance to us and are discussed later.

**Reduction.**—The oxides of some metals may be split up into oxygen and the metal; in other cases not all of the oxygen may be removed, whilst some do not part with their oxygen at all. The process of separating oxygen (whether the whole of it or not) from an oxide is called *reduction*, and a substance capable of doing this (by chemical action) is called a *reducing agent*. This action is rendered possible when the oxygen has a greater affinity for the agent than for the other constituent of the oxide. Strongly heating the oxide may suffice in some instances to remove the whole or part of the oxygen.

**EXPERIMENT 55.**—To reduce mercuric oxide.

Place a few grams of mercuric oxide (red precipitate) in a hard test tube and heat it gently in a Bunsen flame. Soon the oxide will be observed to darken in colour. Remove the tube from the flame and empty out the oxide in a thin layer on to a glass plate. After a time the bright red colour will return, showing that the darkening is not due to burning. Replace it in the test tube and again heat, gently at first and then strongly. Ignite a wood splint, extinguish the flame so that the end is just glowing and introduce it into the mouth of the tube. It bursts into flame and glows brightly as it did in Experiment 16, thus showing that oxygen is being given off. As the heating is continued and more oxygen is released a mirror forms on the inside of the test tube. Allow the tube to cool and then knock out the contents, when globules of metallic mercury will be found amongst the remainder of the oxide. If the mirror is scraped off the sides of the tube with a splint it also will be found to be mercury.

**EXPERIMENT 56.**—To reduce lead oxide.

Repeat the last experiment using red lead instead of mercuric oxide. The red lead is  $Pb_3O_4$  and, as we saw in Experiment 51 it is converted into lead monoxide or litharge ( $PbO$ ) by the removal of

some of its oxygen. If the heating is continued in the presence of a current of air the oxygen is taken up again and red lead re-formed. The monoxide cannot be split up into oxygen and metallic lead by simple heating except by the use of a reducing agent.

**REDUCING AGENTS.**—When carbon is heated in air it combines readily with oxygen to form carbon monoxide ( $2C + O_2 = 2CO$ ) or carbon dioxide ( $C + O_2 = CO_2$  or  $2CO + O_2 = 2CO_2$ ). Heated carbon is therefore in itself a powerful reducing agent, as will be seen from the next experiment, whilst carbon monoxide also acts similarly by taking up further oxygen to form carbon dioxide.

**EXPERIMENT 57.**—To obtain lead from lead oxide.

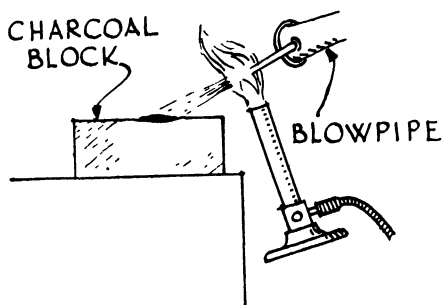


FIG. 77.—Reduction of Lead Oxide.

Drill or scrape a shallow depression in the top of a block of charcoal and place in it a small quantity of red lead. With a mouth blowpipe direct a flame on to the red lead so that the reducing portion of the flame is in contact with it. (See under Combustion, page 125.) The effect of this is gradually to deprive the red lead of its oxygen giving first the yellow litharge and subsequently metallic lead.

Hydrogen acts as a reducing agent by combining with the oxygen of an oxide to form water. Sheets of lead are often joined by “burning” or melting the adjacent edges and allowing them to set together. This is done by means of a blowpipe flame produced sometimes by burning oxygen and hydrogen, the hydrogen preventing oxidation of the surface of the lead due to the heat of the flame.

When metals are heated their combination with atmospheric oxygen is facilitated, for instance in soldering, and to prevent oxidation of the surfaces a reducing agent is used. A reducing agent used in this way, or in the extraction of metals from ores, etc., is called a *flux*.

**EXTRACTION OF METALS FROM ORES.**—As oxygen is such an active element the metals with which it combines are seldom found in a free state in nature. Instead they are combined in some way or other with it as oxides, carbonates, etc., and are freed by processes which include reduction.

Iron is found in various ores as  $Fe_2O_3$  and  $Fe_3O_4$  (oxides) and  $FeCO_3$  (carbonate). The ores also contain other substances as impurities, and these are expelled in the blast furnace by combination with lime and carbon introduced in the form of limestone and coke along with the ore at the top of the furnace. Under the action of blasts of hot air, injected through holes around the base of the furnace, the limestone ( $CaCO_3$ )

splits up into quicklime (CaO) and carbon dioxide (CO<sub>2</sub>). The quicklime or calcium oxide combines with the impurities to form "slag." The carbon dioxide is reduced to carbon monoxide (CO) by the burning of the coke, and this partly reduces the iron oxide to FeO. The intense heat helps in reducing this to metallic iron and this, together with the molten slag, is run off, the slag into trucks or ladles for carting away and the iron into sand moulds to solidify into "pig iron." The production of cast iron, wrought iron and steel from pig iron will not be dealt with here.

Lead occurs mostly as lead sulphide (PbS) and lead carbonate (PbCO<sub>3</sub>). The lead sulphide is heated and takes up oxygen to form lead oxide and lead sulphate. The reactions are:  $-2\text{PbS} + 3\text{O}_2 = 2\text{PbO} + 2\text{SO}_2$  (sulphur dioxide gas) and  $-\text{PbS} + 2\text{O}_2 = \text{PbSO}_4$ . Subsequently the lead oxide combines with more lead sulphide to give metallic lead:  $-2\text{PbO} + \text{PbS} = 3\text{Pb} + \text{SO}_2$ , and the lead sulphate also combines with sulphide:  $-\text{PbSO}_4 + \text{PbS} = 2\text{Pb} + 2\text{SO}_2$ .

The lead carbonate is heated to form lead oxide:  $-\text{PbCO}_3 = \text{PbO} + \text{CO}_2$  and then treated as before.

Zinc is obtained from zinc sulphide (ZnS) and zinc carbonate (ZnCO<sub>3</sub>) by heating to form zinc oxide. Thus  $2\text{ZnS} + 3\text{O}_2 = 2\text{ZnO} + 2\text{SO}_2$  and  $\text{ZnCO}_3 = \text{ZnO} + \text{CO}_2$ . In both these instances the oxide is then reduced by heating with coke and the molten zinc vaporized and condensed.  $\text{ZnO} + \text{C} = \text{Zn} + \text{CO}$ .

Tin occurs as an oxide SnO<sub>2</sub>, and after preliminary treatment to remove impurities it is reduced in a furnace in the presence of carbon.  $\text{SnO}_2 + 2\text{C} = \text{Sn} + 2\text{CO}$ .

There are several ores containing copper but as a rule their composition is complex and the treatment for extraction rather involved. Broadly speaking, however, they may be said to comprise copper sulphide and copper carbonate, but the processes are not so simple as in the case of lead. There is one ore, although the least common, which consists of oxide of copper, Cu<sub>2</sub>O.

## 2. OXYGEN.

The reduction of an oxide provides a simple means of obtaining oxygen in small quantities; there are more convenient methods of preparing it on a larger scale. For industrial use it is bought in steel cylinders in which it is stored under high pressure. It is prepared commercially by the distillation of liquid air and by the electrolysis of water. For laboratory purposes it is usually obtained from potassium chlorate by heating strongly to drive off the oxygen, leaving potassium chloride:  $-2\text{KClO}_3 = 2\text{KCl} + 3\text{O}_2$ . The process is simplified by adding 1 part by weight of manganese dioxide to 5.33 parts by weight of potassium chlorate and heating less strongly. The manganese dioxide acts as a

*catalyst* or *catalytic agent* and takes little or no part in the chemical process. The mixture mentioned is generally called "oxygen mixture," and the gas is collected by the displacement of water, as will be seen from the experiment. This method is used to collect any gas which is not too soluble in water.

EXPERIMENT 58.—To prepare oxygen from oxygen mixture.

Weigh out the ingredients in the correct proportions, 1.5 gm. of manganese dioxide and 8 gm. of potassium chlorate should be sufficient. Fit up the apparatus shown in Fig. 78, filling the pneumatic trough so that the shelf is just covered. Fill a gas jar with water, cover it with a ground glass jar cover and invert it so that when its mouth is under water the cover can be slid away. Place the inverted jar, still full of water, on the shelf but do not insert the delivery tube yet. Place the hard glass flask containing the oxygen mixture on the tripod, interposing an asbestos pad or gauze, so as to avoid the possibility of cracking the flask, connect the delivery tube and apply heat by means of the Bunsen flame. Immerse the end of the delivery tube in the water in the trough, but not under the shelf until it has been bubbling for a few seconds; the first few bubbles are of air driven from the flask and tube. Then insert the end of the tube through the shelf and gas will bubble up into the jar, displacing the water downwards into the trough. When all the water has been displaced from the jar slide a ground glass cover under it and remove jar and cover, placing them aside in an upright position. Collect several more jars of gas in a similar manner. The burner must not be removed whilst changing jars, or water from the trough may be drawn up into the flask and put a violent stop to the experiment.

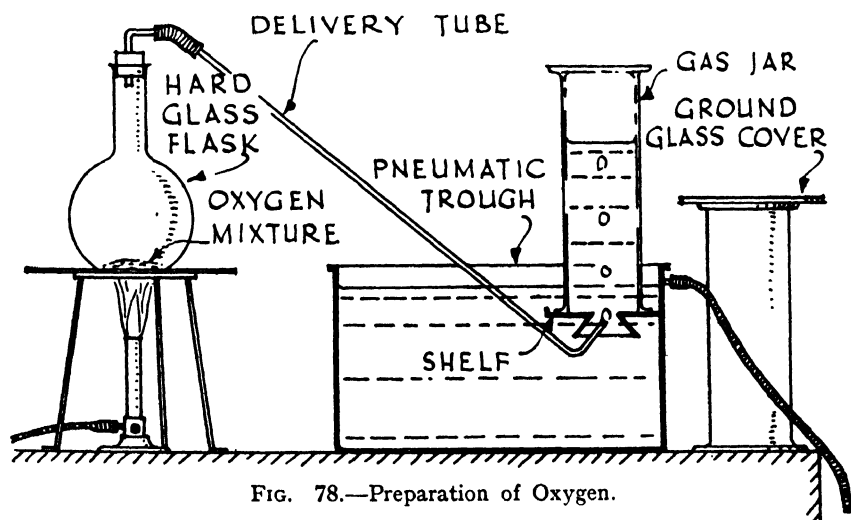


FIG. 78.—Preparation of Oxygen.

It will be noticed at once that the oxygen is colourless and odourless. If we plunge a glowing taper or splint into the jar we notice that the gas

does not burn, although it causes the taper to burn much more brightly, and thus is a supporter of combustion.

### 3. NITROGEN.

In Experiments 53 and 54 we had left in the test tube a quantity of nitrogen, the inactive constituent of air, equal in volume to about four-fifths of the air. If nitrogen is required for experimental purposes there are better ways of preparing it, one of which forms the subject of the next experiment. Here we obtain nitrogen from the air by analysis.

**EXPERIMENT 59.**—To prepare nitrogen from air.

Into a  $\frac{1}{4}$ -in. diameter glass combustion tube place a roll of copper gauze or a quantity of clean copper turnings and support it by stands as shown in Fig. 79. Fit corks and tubing as shown, one end connected to the *top* of an aspirator and the other to a delivery tube arranged so as to collect a gas. By means of a spread Bunsen flame heat the copper to redness and then turn on the water supply to the bottom of the aspirator, very slightly. Water entering the aspirator pushes out the air in a steady stream over the red hot copper. The oxygen is taken up by the copper to form copper oxide, and the nitrogen continues along the delivery tube to be collected in the usual way. The aspirator must be watched carefully and no water permitted to enter the hot tube.

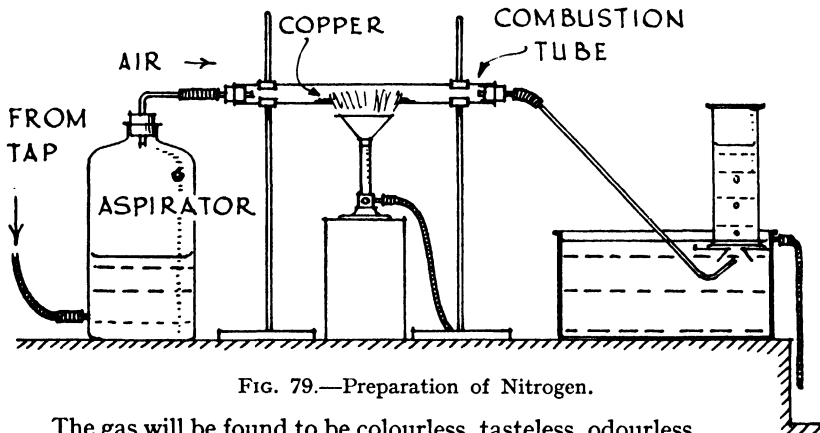


FIG. 79.—Preparation of Nitrogen.

The gas will be found to be colourless, tasteless, odourless, only very slightly soluble in water, and only slightly lighter than air. It does not burn and does not support combustion. All these characteristics will be seen to be negative rather than positive, emphasizing the inactivity of nitrogen. Its function appears to be that of a diluent only, oxygen by itself being too "concentrated" for respiration in plant and animal life. Nitrogen is of great importance in the plant world and in combination with hydrogen goes to form ammonia and many important ammonia compounds.

#### 4. COMBUSTION.

Combustion, or burning, is a process of rapid oxidation brought about by the chemical combination of oxygen with some other gas or gases. It is distinguished from ordinary oxidation such as the rusting of iron, etc. by reason of the fact that light and considerable heat (flame) are produced.

When it occurs under normal conditions it is called "spontaneous combustion"; phosphorus left in the air in normal temperatures bursts into flame, and for this reason has to be stored under water. Usually, however, even when the substance combining with the oxygen is gaseous under ordinary conditions, their temperature must be raised before combustion will take place. This process is called "ignition" and we are said to "ignite" the substance. Solids and liquids must be "volatilized" (converted into gas) before they will burn, for instance paraffin wax will not burn whilst it remains solid, nor will liquid paraffin.

EXPERIMENT 60.—To show that liquid paraffin does not ignite.

Pour out some paraffin into a dish, light a wood splint or match and thrust it into the paraffin. The splint is immediately extinguished because the paraffin cuts off the ordinary supply of oxygen, and is itself unable to volatilize or vaporize in time to continue the combustion. Petrol volatilizes at a lower temperature than paraffin, and if we were to repeat the experiment with petrol, (which is not advised), we should, as is well known, "set it alight."

EXPERIMENT 61.—To observe the process of igniting paraffin wax.

Light a wax candle and observe how the wax first melts to liquid and is then drawn up the cotton wick by capillarity. Notice that the lower portion of the wick, although saturated with liquid paraffin, does not burn; only after travelling still further up the wick does volatilization take place and then the vapour is able to combine with the atmospheric oxygen to produce a flame. Extinguish the flame by blowing; the paraffin vapour will continue to issue from the wick for a few seconds until its temperature falls below the point of volatilization.

If we heated a dish of paraffin wax it would melt, then volatilize, and the gas given off would burn in quantity if ignited. The wick of the candle or of a paraffin lamp is used as a convenient means of controlling the rate of volatilization and burning.

Paraffin blowlamps and pressure stoves have an arrangement whereby the liquid is made to pass through tubes heated by preliminary combustion of spirit in a shallow tray. This pre-heating vaporizes the paraffin so that it issues from the jet or burner as a gas and not as liquid. By suitably admitting air a blue, smokeless flame is produced, one in which combustion is more complete than would otherwise be the case.



**EXPERIMENT 62.**—To show that oxygen is used in combustion.

Fix a short wax candle to a thin piece of wood or cork, float it on the surface of water in a dish or trough, light it and place an inverted gas jar over it, immediately marking the water level on the side. After a few seconds the flame will be extinguished and the water level in the jar will rise. Mark this level on the jar and compare the result with that of Experiment 53, page 109.

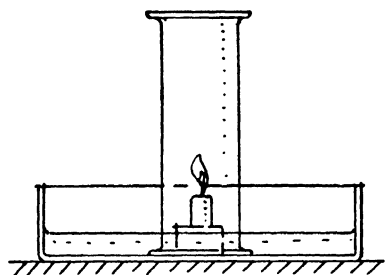


FIG. 80.—Disappearance of Oxygen during Combustion.

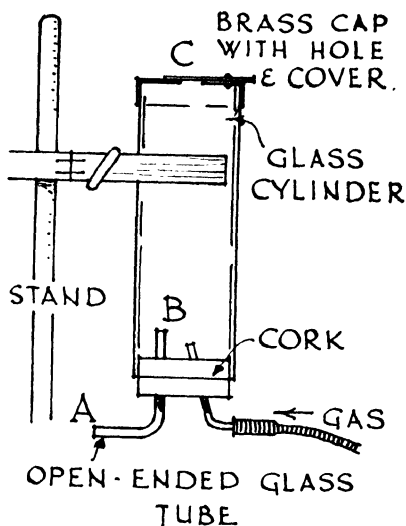


FIG. 81.—To Show the Nature of Combustion.

Substances which normally burn in air therefore cannot do so unless a supply of oxygen is available. A flame introduced into a closed vessel of coal gas, hydrogen, petrol or other inflammable substance, if it were possible to do so without admitting air or oxygen, would be extinguished just as it was in the paraffin in Experiment 60.

**EXPERIMENT 63.**—To show the real nature of combustion.

The apparatus shown in Fig. 81 comprises a glass cylinder open at the top and bottom. On the top is a brass cap with a hole in the centre, C, and a hinged brass lid which may cover the hole at will. Into the bottom of the cylinder is fixed a cork through which two glass tubes are fitted as shown, the smaller one being connected to the gas supply.

Close the brass lid and turn on the gas, waiting until it issues from the open end of the tube at A. Apply a light to A and a flame will be produced, the coal gas "burning in air."

Then open the brass lid so as to uncover the hole C. Air is immediately drawn in at A and the flame is transferred to B. This is air (or rather the oxygen of the air) "burning in coal gas." Next apply a light to C and the gas issuing from the hole will ignite. This is again gas "burning in air."

From this experiment it will be seen that it is really no more correct to say that gas or any other inflammable substance " burns " as it would be to say that air or oxygen " burns."

" SELF-CONTAINED " COMBUSTION.—Some special substances are produced which will burn without the aid of atmospheric oxygen. Incendiary bombs and shells are made in such a way that the necessary oxygen is contained within the material or apparatus itself. These will therefore burn under water or in any other position where atmospheric oxygen has no access, and they thus cannot be extinguished by the usual fire-fighting methods. The most that can be done is to prevent the spread of the conflagration which they may cause. Smothering them with water spray assists combustion and causes them to burn out more rapidly ; covering with sand or earth merely hides their brilliant light, they will still burn out as nothing can be done to remove their oxygen supply.

When combustion is instantaneous it is referred to as " explosion." It is accompanied by an extremely rapid expansion of the gases produced (blast) and a consequent violent sound or report. Explosive substances are invariably made on the same principle as incendiary substances, *i.e.* all the agents necessary for their action are contained in the substance itself.

FIRE-RESISTING CONSTRUCTION.—In the ordinary way a sufficient supply of air is necessary for combustion, so that if a large building is constructed in compartments with all doorways and other intercommunicating openings fitted with automatically closing fire-resisting doors, and all windows glazed with fire-resisting glass, the chances of a fire started in one part spreading into a general conflagration is remote. Such requirements form the subject of certain regulations for fire-resisting buildings, and in conjunction with an automatically operated " sprinkler " installation have saved many important buildings from destruction by fire.

Fire-resisting doors are constructed of steel interleaved with asbestos, and arranged to slide into position upon a fusible wire becoming melted by local heat. Sprinklers work on the same principle, being usually self-operated individually, so that stock in parts of the building remote from the fire is not spoilt by water.

Fire-resisting glazing is usually some form of wired glass, two thicknesses of special glass with metal mesh embedded between and the whole fused together. The metal is such as will withstand very high temperatures and the effect of intense heat, even flames, upon it is merely to crack the glass without it falling in fragments. Certain types of electro-copper glazing are also accepted as fire-resisting.

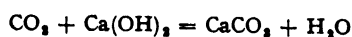
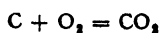
The building materials, and the form of construction, must be chosen for their fire-resisting qualities, and the regulations include a schedule of suitable materials, and conditions under which they must be used. It is interesting to note that some materials which are in themselves incombustible are not necessarily fire-resisting, whilst others which are inflammable can be fire-resisting. Steelwork, for instance, must be protected from intense heat by encasing it in suitable concrete or plaster of certain minimum thickness, or its violent expansion and buckling may lead to collapse, and further spread of the fire. Timber, on the other hand, may be reasonably fire-resisting if used in adequate thicknesses and in such a way that no arrises are exposed to the flames. A flat soffit or ceiling of wood, without open joints, takes a long time to ignite. Large section wood beams with arrises well rounded or chamfered similarly offer good resistance, the surfaces merely becoming charred to a small depth, and thus reducing access of air to the unaffected wood beneath. The domestic fire offers an illustration of this point; the thinner the firewood is split the easier it is to light the fire. A log or large block does not burn readily, even on a well-established fire; similarly coal dust is put on in order to "damp down" the fire, doing so by offering obstruction to the flow of air through the fire, whilst the effects of "forced draught" in accelerating combustion are well known.

Several well known recent store buildings are of protected steel frame construction, although the floors are of soft-wood. These are about 7-in. thick, composed of rectangular joist sections spiked together to form solid flooring units, and placed in position much as are precast hollow concrete beam units. Such a floor is lighter and less costly than concrete, and in such a form more fire-resistant than most concrete. The only satisfactory fire-resistant concrete is one of which the coarse aggregate is hard brick; other concretes, although incombustible, are adversely affected in other ways.

### THE CHEMISTRY OF COMBUSTION.

**EXPERIMENT 64.**—To show that the combustion of carbon compounds produces an oxide of carbon.

Fix a short splinter of wood to a deflagrating spoon, ignite it, and lower it into a gas jar containing air or oxygen, holding the brass plate down firmly. Remove the spoon, pour into the jar a little lime water, fit a ground glass jar cover and shake well. The lime water, previously clear and colourless, turns "milky." Lime water is a weak solution of calcium hydroxide,  $\text{Ca(OH)}_2$ , which is converted into calcium carbonate,  $\text{CaCO}_3$  (visible as a cloud of minute grains) by combination with carbon dioxide gas evolved by the combustion.



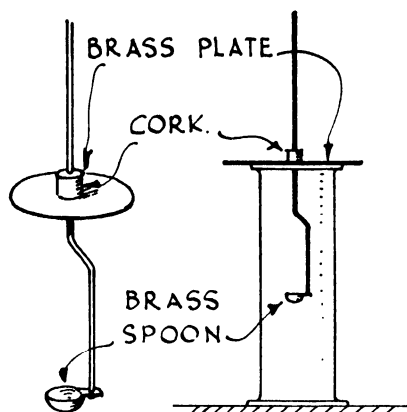
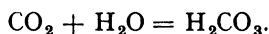


FIG. 82.—An Oxide produced by Combustion.

Some of the carbon dioxide dissolves in the water to give carbonic acid (Carbon dioxide is sometimes called "carbonic acid gas.") If we repeat the experiment and add water instead of lime water, then dropping into the jar a piece of blue litmus paper, it turns slightly red, so indicating that the solution is a weak acid. The reaction is :—



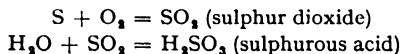
The use of litmus as an "indicator" is explained in Chapter VIII. Carbon dioxide is dealt with fully in Chapter IX, but one of its properties has been noticed here, its chemical combination with calcium

oxide,  $\text{CaO}$  to form calcium carbonate,  $\text{CaCO}_3$  or chalk. Most organic substances are, or contain, compounds of carbon, and their decomposition results in the formation of carbon dioxide.

**EXPERIMENT 65.**—To show that the combustion of sulphur produces an oxide of sulphur.

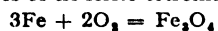
Place a little flowers of sulphur in a deflagrating spoon and hold it in a Bunsen flame until the sulphur burns with a pale blue flame and gives off white fumes. Now remove the glass cover from a jar of oxygen, plunge the spoon into it and press the plate tightly down. The sulphur immediately burns more vigorously and the jar fills up with fumes. When the burning ceases quickly remove the spoon, pour in a little water, replace the glass cover and shake the jar; the fumes disappear. Now drop a piece of blue litmus paper into the jar and it is seen to turn red, indicating that the solution in the jar is an acid, as in the previous experiment.

The reactions are :—



**EXPERIMENT 66.**—To show that the combustion of iron produces an oxide of iron.

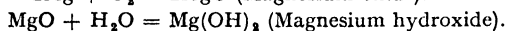
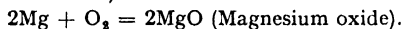
Prepare a jar of oxygen and, through a funnel and tube, introduce sufficient dry sand to well cover the bottom. Then coil a piece of thin iron wire, attach a piece of wood match to one end, attach the other end of the coil to a deflagrating spoon, light the match and lower the spoon into the jar. Press down the brass plate. When the flame reaches the iron wire the wire will burn (if thin enough), forming globules of tri-ferric tetroxide, which are insoluble in water.



Compare with Experiment 51.

**EXPERIMENT 67.**—To show that the combustion of magnesium produces oxide of magnesium.

Repeat Experiment 65 but with a small piece of magnesium in the spoon. Add water, shake up and test with *red* litmus paper. It turns blue, indicating that the solution is alkaline (not acid as with sulphur and carbon).



Magnesium hydroxide is known as “milk of magnesia” and is used medicinally as an antacid.

From these experiments we confirm that combustion is merely a rapid oxidation and that, when soluble in water, the oxides of non-metals are acid and the oxides of metals are alkaline. The properties of acids and alkalis are dealt with in Chapter VIII.

**FLAMES AND THE BUNSEN BURNER.**—Paraffin wax, paraffin oil and coal gas all contain compounds of hydrogen and carbon which are called “hydro-carbons” (not to be confused with “carbo-hydrates”—these are compounds of carbon, hydrogen and oxygen in organic substances.)

A candle, an oil lamp or stove and a gas jet all burn with a bright or luminous flame. They also give off a certain amount of smoke. They are luminous because they are made up of incandescent particles of solid carbon, and the black smoke is composed of minute particles of unburnt carbon. Lamp black, the water and oil colour pigment, is produced by allowing an oil flame to impinge on a cold surface; the smoke is deposited as fine soot, so fine that no grinding is needed to make it suitable for use in paints.

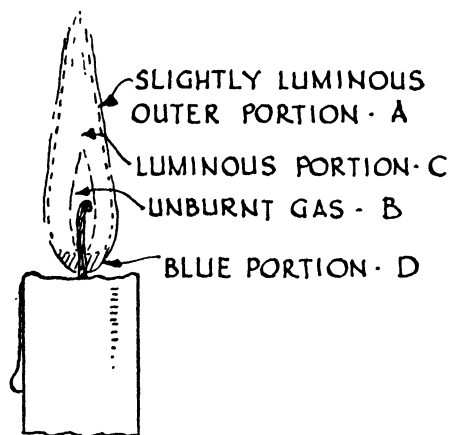


FIG. 83.—The Candle Flame.

In such a flame the atmospheric oxygen only has access to the outside, where it burns as a pale, almost non-luminous mantle A (see Fig. 83). The portion of the flame which is innermost, B, consists of unburnt gas since it receives no oxygen. The middle and largest part of the flame, C, is the luminous portion; here there is sufficient air only to separate the gas into carbon and other constituents. As this burning gas travels upwards and outwards it gradually

reaches the area of good oxygen supply and at the outside burns

well as described, the solid particles of carbon combining with the oxygen to form carbon dioxide gas ; or if the oxygen supply is insufficient, even on the outside, they form smoke. At the lowest part of the flame a rising current of air impinges upon it and so forms a blue portion, D, in which combustion is complete.

To produce a smokeless flame it is necessary to increase the oxygen supply by fitting a chimney and providing inlet holes at the base ; to render the flame non-luminous in addition a supply of oxygen must be mixed with the unburnt gas so that no solid carbon particles enter the flame. The Bunsen burner, the gas ring, and the incandescent mantle burner are designed to give a hot, blue, non-luminous and non-smoky flame.

The Bunsen burner, shown in section in Fig. 84, and universally used for laboratory purposes, is a simple arrangement whereby the gas supply issues upwards through a jet at the base of a vertical tube. By the side of the jet are one or several air inlet holes which can be adjusted for size by a rotating sleeve. When gas issues under pressure through the jet the air pressure around it is reduced and air is consequently forced in (by atmospheric pressure) through the air inlets and mixes with the gas travelling up the tube. When the air inlets are fully closed only gas reaches the top of the tube, where it burns with a luminous flame, insufficient air for complete combustion being available. Upon opening the air inlets gas and air are mixed, and when sufficient air is admitted the

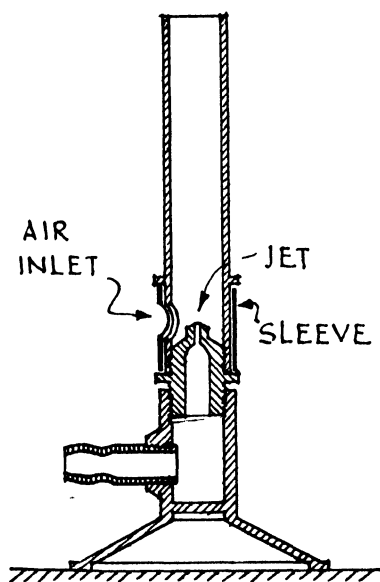


FIG. 84.—Section through Bunsen Burner.

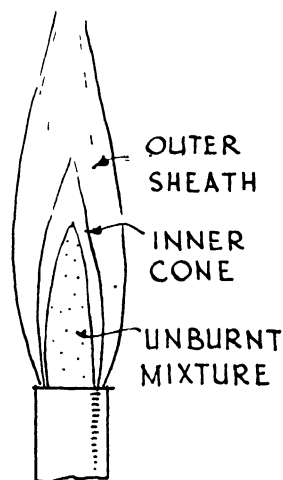


FIG. 85.—The Bunsen Flame

flame becomes a "blue" flame, non-luminous and giving off no smoke. The bunsen flame is illustrated in Fig. 85, and comprises an inner portion of gas-air mixture (with insufficient air for combustion), dark in colour, around this a faintly distinguishable inner cone of flame where combustion is just commencing, and an outer sheath, the main portion of the flame, reddish blue in colour and in which may be observed occasional incandescent carbon particles giving a slightly luminous appearance. Outside air has access to this last portion and when the gas and air are mixed in the correct proportions combustion here is almost perfectly complete. The temperature of the flame clearly varies in different parts, the innermost portion of unburnt mixture having a temperature so low as to take a few seconds to ignite a match.

#### EXPERIMENT 68.

Pierce a wood match with a pin about  $\frac{3}{4}$ -in. from the head and insert the match in the tube as in Fig. 86 before lighting the burner. Now light the gas and observe the effect upon the match head.

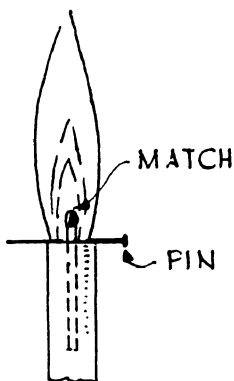


FIG. 86.  
Showing Low Temperature  
of Inner Cone of Bunsen  
Flame.

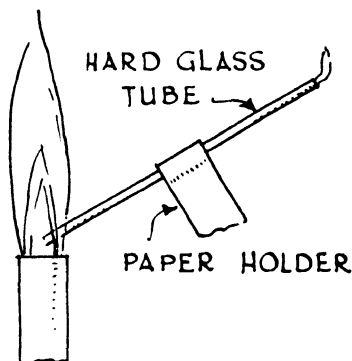


FIG. 87.—Showing Nature of Inner-  
most Portion of Bunsen Flame.

#### EXPERIMENT 69.

Hold a length of fine bore hard glass tubing by a piece of folded paper so that one end of the tube is inside the innermost portion of the flame, and apply a light to the outer end. The unburnt gas mixture travels up the tubing and burns with a small flame. Now move the other end higher up the Bunsen flame and the small flame will disappear.

#### EXPERIMENT 70.—To show the formation of water on burning coal gas in air.

Fit up the apparatus shown in Fig. 88 and allow a small flame to impinge upon the cold base of the flask. A mist will be seen to form upon it, which collects into drops which may be collected in a beaker and are found to be water.

The coal gas contains hydrogen, and this has combined with atmospheric oxygen to form water :—



(See also Experiment 75, page 128.)

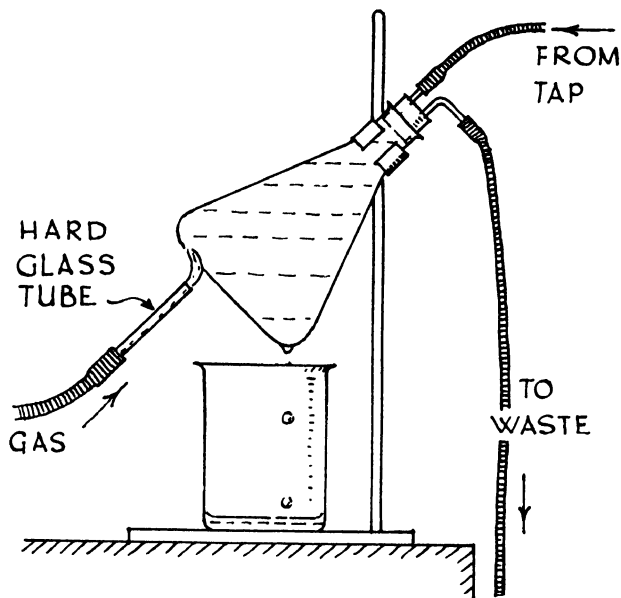


FIG. 88.—Formation of Water by burning Coal Gas in Air.

The hottest part of the Bunsen flame is just above the top of the inner cone where it may reach 1,500 deg. Cent. Up to a certain point admitting more air produces a hotter flame. Such a mixture burns more rapidly, and when the air inlets are fully open and the gas supply turned low the mixture may burn downwards faster than the gas-air mixture travels upwards in the tube. When this occurs the burner "strikes back" and the gas burns at the jet itself with a yellow flame; a smell of acetylene will also be noticed, this being one of the minor constituents of coal gas.

**THE BLOWPIPE.**—This is similar in principle to the Bunsen burner but a hotter flame is produced by forcing a jet of air into the flame under pressure. Around the inner cone the flame has reducing properties owing to its shortage of oxygen, whilst on the outside of the outer sheath there is an excess of oxygen and this portion thus has oxidizing properties. By suitably regulating the air (or pure oxygen) supply, the reducing and oxidizing properties can be varied to suit the work in hand, such as lead "burning," etc. The ordinary Bunsen flame has these properties too, but to a smaller degree. In the "oxy-acetylene" blowpipe temperatures up to 2,500 deg. Cent. can be obtained by forcing oxygen into an acetylene flame.



## CHAPTER VIII

### WATER

1. *Composition of Water.*
2. *Hydrogen.*
3. *The Solvent Action of Water.*
4. *Distillation.*
5. *Deliquescence and Efflorescence.*

#### 1. COMPOSITION OF WATER.

Water is the commonest liquid and is as important as air, both in its action in rendering the earth suitable to sustain life and in the actual sustenance of life. Natural water is, however, not pure water as it always contains dissolved substances. We are for the moment concerned with pure water.

EXPERIMENT 71.—To note the effect of water upon heated iron.

Holding a piece of bright iron wire with a pair of crucible tongs, heat it to redness and then plunge it into some pure water. Then examine the wire and it will be found to be covered with a black scale which appears to be the same substance as that formed on the iron in Experiments 50 and 51. Actually it can be shown to be the same substance, tri-ferric tetroxide,  $\text{Fe}_3\text{O}_4$ .

From this we see that oxygen is present in the water ; further we see that it must be a constituent of water, since we used pure water that contained no oxygen in solution. Let us now perform the experiment in such a way as to see what else occurs besides the formation of an oxide.

#### EFFECT OF WATER UPON METALS.

EXPERIMENT 72.—To note the effect of red hot iron upon water.

We shall use water in the form of steam, generated in a copper boiler. Fit up the apparatus shown in Fig. 89. The wrought-iron tube contains iron filings spread over 6-in. or so of its length and is heated by a spread Bunsen flame. After the tube has become red hot pass steam over the iron filings, and bubbles of gas will be seen to escape from the end of the delivery tube. Before placing the gas jar to collect it, collect some of the gas bubbles in test tubes, testing with a burning splint from time to time. When they cease to explode collect two jars of the gas, placing a ground glass plate over the mouth of each before removing it. Do not discontinue the steam supply before removing the delivery tube from the water, or water may be forced back into the red hot tube.

Holding the first jar upside down, remove the cover plate and introduce a burning splint. The gas will be seen to burn quietly with a pale blue flame but the splint will be extinguished.

Keep the second jar upright on the table, remove the plate and hold a burning splint to it. It will explode with a loud report, but

is quite harmless as it is not confined and the walls of the jar are thick enough to prevent damage. The gas had partly escaped and its place taken by air, the mixture being explosive. After the iron tube has cooled knock out some of the contents and the filings will be seen to have turned into a mass of the black iron oxide.

The gas obtained in this experiment is Hydrogen, one of the elements given in Table 5, page 103.

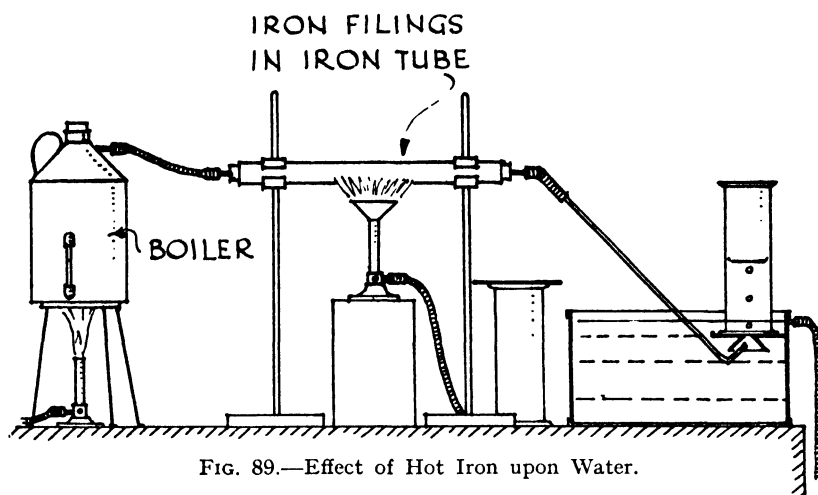


FIG. 89.—Effect of Hot Iron upon Water.

EXPERIMENT 73.—To observe the effect of water upon magnesium.

Scrape a piece of magnesium ribbon so that its surface becomes bright and place it under water in a dish. After a week inspect it and the metal will have become darker in colour, bubbles of gas adhering to it and escaping to the surface on being touched or agitated. These are bubbles of hydrogen.

If we were to repeat Experiment 72, using magnesium instead of iron we should be able to collect hydrogen in the same way, and we should have oxide of magnesium,  $MgO$ , left in the tube.

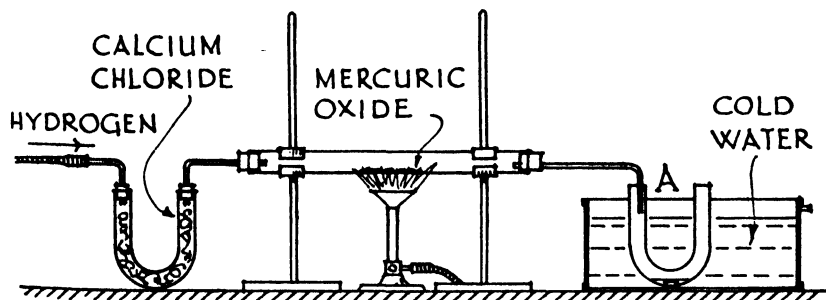


FIG. 90.—Formation of Water by action of Hydrogen upon an Oxide.

**EXPERIMENT 74.**—To observe the effect of water upon sodium.

Invert a gas jar of water on the shelf of a pneumatic trough full of water and introduce a small piece of metallic sodium (about  $\frac{1}{4}$ -in. across) into the water below the mouth of the jar. This can be done by holding it between the points of a pair of crucible tongs and plunging it as rapidly as possible under the shelf. Violent action starts immediately, the sodium becomes a hissing liquid globule which rises to the top of the water, the water level in the jar slowly falls and the sodium disappears in a very short time. Slide a cover plate over the mouth of the jar, and test the gas as in Experiment 72. It will be found to be the same gas, hydrogen.

These experiments show that oxygen and hydrogen are both contained in water but do not prove that these are the only elements present. To do this we must see whether we can produce water from the two gases alone. If we merely admit oxygen into a jar of hydrogen, or *vice versa*, nothing apparently happens, at least we get no water as the result. Something different is therefore needed to start the chemical action if such action is possible.

#### SYNTHESIS OF WATER.

**EXPERIMENT 75.**—To show the action of hydrogen upon oxides.

Fit up apparatus to prepare some hydrogen, either as in Experiment 72 or preferably as shown in Fig. 91. Pass this gas through a glass U tube filled with calcium chloride. This substance absorbs any moisture so that the hydrogen leaves the U tube perfectly dry. Then lead it as shown in Fig. 90 through a hard glass tube in which mercuric oxide is heated strongly by means of a spread Bunsen flame, and connect the outlet tube to an empty U tube standing in a trough of cold water.

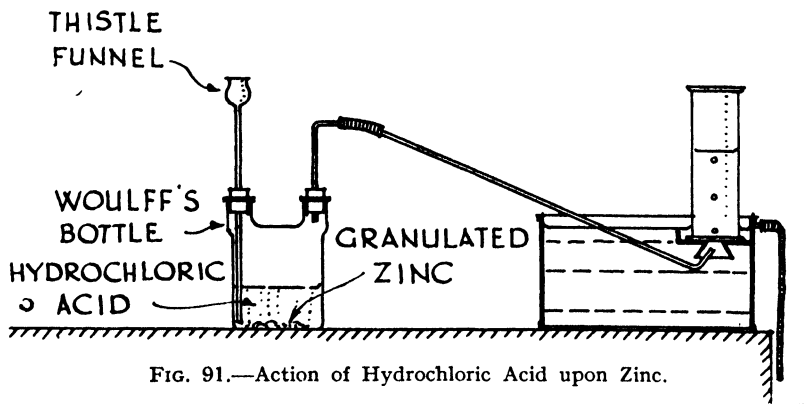


FIG. 91.—Action of Hydrochloric Acid upon Zinc.

Several precautions are necessary, as we have seen that hydrogen is explosive when mixed with air. Firstly the apparatus must be airtight, so all connections should be checked; secondly before

heating the oxide and connecting the collecting U tube the gas issuing at A should be tested with a flame to see whether it burns quietly, only then should heat be applied to the oxide.

The mercuric oxide will be observed to undergo the same change as in Experiment 55, page 112, oxygen being given off and metallic mercury left in the tube. After a time examine the U tube in the trough and a small quantity of colourless liquid will be seen to have been collected. This may be shown to be pure water. The hydrogen admitted to the combustion tube has combined with the oxygen driven off from the oxide to form steam, this passing to the cold U tube where it has condensed into water. (See also Experiment 70, page 124.)

We have proved, therefore, that water consists of oxygen and hydrogen in chemical combination, but as yet we have no indication of their proportions. An experiment which confirms the composition of water and at the same time shows the proportions in which the two gases are present may easily be carried out if the necessary apparatus is available. The process is the synthesis of water and the apparatus is called a "eudiometer"; there are several types but they work on the same principle. Essentially it is a long, graduated glass tube with two platinum electrodes fused into it near one end, which is closed or is provided with a tap so that it may be closed. It is filled with mercury and inverted so that its open end is submerged in mercury in a vessel, or alternatively it may be in the form of a U tube filled with mercury. Hydrogen and oxygen are then introduced by means of a tap into the vacuum at the top of the inverted type, or similarly in the U tube type by withdrawing some of the mercury from a tap at the bottom. By means of a battery and coil, a spark is now made to pass between the electrodes and the gases explode. (This is an instance in which electricity is the agent used to commence chemical action.) At the same time the mercury rises in the tube, showing that some of the gas mixture has disappeared, and droplets of water appear on the inside of the tube.

If the experiment is performed with one part by volume of oxygen and two parts by volume of hydrogen, the explosion is severe and no gas is left. If the gases are admitted in other proportions the violence of the explosion is reduced and a surplus of one or other gas (the one which was in excess) is left.

**ANALYSIS OF WATER.**—As a further check, the foregoing process may be reversed and water analysed or decomposed into its constituents. This also requires a special apparatus which again is unlikely to find a place in a Building laboratory. It is called a "voltameter," and in its usual form comprises a large glass U tube with taps at the extremities of the limbs. At the bottom of the bend another long glass tube with a smaller bend at its foot is joined to it so that the whole forms a single

vessel. Near the bottom of each arm of the U is a platinum electrode with terminals to be connected to a battery. The whole apparatus is filled with water that has a slight addition of acid (to facilitate the conduction of the electrical current), the two taps closed and more water added at the top of the third tube, which rises to a higher level than the others. Upon passing a steady current through the water via the two electrodes gas is seen to rise from each and collect at the top of each arm of the U. The volume of gas collecting in one of them will be seen to be approximately twice the volume of that collecting in the other. (It will not be exactly twice because oxygen is slightly more soluble in water than is hydrogen.) The two gases may be tested and will be found to be oxygen and hydrogen.

This electrical method of analysis is called "electrolysis" and is used among other things to decompose sodium and potassium hydroxides and so to isolate the metals sodium and potassium.

**CHEMICAL PROPERTIES OF WATER.**—We learn then as the collective result of our experiments that water is a chemical compound of two elements, oxygen and hydrogen, in the proportion by volume of 1 : 2, or by weight 8 : 1. It is decomposed by some metals, by a few in the cold state but by a greater number when heated, and in all cases hydrogen is set free, leaving usually an oxide of the metal (but occasionally a hydroxide). When it combines with oxides of non-metallic elements it forms acids and with oxides of metallic elements it forms alkalis. We saw also (Chapter I) that it combines with some substances to form crystals, such crystals containing water of crystallization.

## 2. HYDROGEN.

So far we have found that hydrogen is contained in water, that it combines with the oxygen of certain oxides to form water, that it is released from water by certain metals and that it may be combined with oxygen by exploding the two gases or released from water by an electric current. It is used as a reducing agent owing to its readiness to combine with oxygen, so removing unwanted oxide, and also in welding on account of the high temperature attained by burning it in conjunction with oxygen in a blowpipe. It can be liquified at a temperature of  $-253$  deg. Cent. and is obtainable commercially in highly compressed form in steel cylinders.

**PREPARATION AND TESTING OF HYDROGEN.**—For use in the laboratory there are more convenient methods than those given in Experiments 72, etc. Acids, as will be seen later, contain hydrogen and most acids combine readily with certain metals, hydrogen being released in the process.

**EXPERIMENT 76.**—To prepare hydrogen by the action of acid upon zinc.

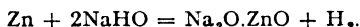
Place a small quantity of granulated zinc in a Woulff's bottle fitted with a thistle funnel and a glass outlet tube. (A large flask

with a two-hole bung may be used if preferred.) See that the funnel tube reaches almost to the bottom of the flask so as to form a seal when the acid is introduced. Add dilute hydrochloric acid, or alternatively cover the zinc and form a seal with water and then add concentrated acid. Bubbles of gas will be seen to rise from the zinc, and after all air has been driven from the apparatus collect several jars of the gas in the manner previously described.

Granulated zinc is used because it offers a large surface to the action of the acid. It is produced by pouring molten zinc into water. The action in Experiment 76 is:  $\text{Zn} + 2\text{HCl} = \text{H}_2 + \text{ZnCl}_2$ , the zinc chloride left in the flask being the flux used in soldering. Sulphuric acid may be substituted for the hydrochloric acid, zinc sulphate then remaining in the flask together with any excess of acid.

**EXPERIMENT 77.**—To prepare hydrogen by the action of sodium hydroxide upon zinc.

Place some granulated zinc in a flask together with a solution of sodium hydroxide. Heat the flask as shown in Fig. 92 and, observing the usual precautions, collect the gas given off. The action in this case is:—



$\text{Na}_2\text{O} \cdot \text{ZnO}$  is sodium zincate or sodium zinc-oxide.

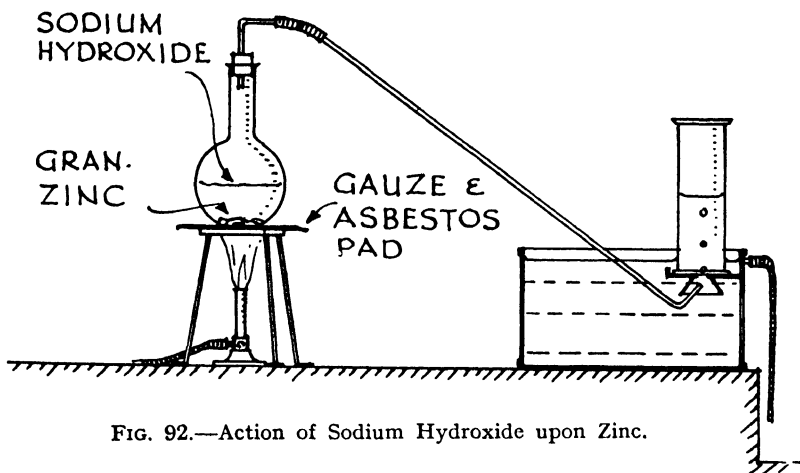


FIG. 92.—Action of Sodium Hydroxide upon Zinc.

We saw from Experiment 72 that hydrogen is highly inflammable, burning quietly when pure but exploding violently when mixed with oxygen. We shall now see that in spite of this it does not support combustion.

**EXPERIMENT 78.**—To show that hydrogen is not a supporter of combustion.

In a position free from draughts hold a jar of hydrogen mouth downwards and remove the cover. Then apply a burning splint to the mouth of the jar and the gas will commence to burn. Push the splint well up into the jar and it will be extinguished.

**EXPERIMENT 79.**—To show the low density of hydrogen.

Hold another jar of hydrogen in a similar manner for some time and then apply a burning splint. Very little of the gas appears to have escaped. Place a further jar of hydrogen upright on the table and remove the cover. After a few seconds apply a burning splint. It will be found that no hydrogen remains in the jar.

Take one jar full of hydrogen and one empty jar. Holding the empty jar mouth downwards in one hand, with the other remove the cover from the full jar and hold its mouth sideways up to the first one for a few moments. Then put down the second jar and, taking a splint ignite it and apply it to the previously empty jar. A slight explosion will show that some of the hydrogen from the full jar had risen and displaced some of the air from the upper one. It had in fact been poured upwards.

This experiment shows that hydrogen is less dense than air. It is actually the "lightest" gas, and thus the "lightest" substance known. For this reason it has been largely used for filling balloons and dirigibles in spite of the great disadvantage of its inflammability.

In Experiment 70, page 124, we formed water by the combustion of coal gas in air. If the experiment were to be repeated with hydrogen we should get the same result, this being a further instance of the synthesis of water.

### 3. THE SOLVENT ACTION OF WATER.

Solid-liquid solutions have been dealt with in Chapter I, Section 4, and it was said there that water is the principal solvent with which we are concerned. In nature water evaporates from the surface of oceans and other sheets of water, is absorbed by the atmosphere, and upon cooling forms clouds of condensed water which may for various reasons coalesce into drops sufficiently large to fall to the earth as rain. On a porous surface the rain is mostly absorbed (some is of course re-evaporated under suitable atmospheric conditions) and sinks downwards to collect ultimately at some level where its further downward movement is prevented by strata of impervious earth.

During its descent from the clouds it comes into contact with, and dissolves, various gases contained in the atmosphere. Subsequently, during its percolation through the ground, it dissolves organic and mineral matter in large quantities. The water obtained from springs, wells and boreholes is thus far from being pure water, in certain cases the dissolved substances giving the water medicinal properties. River and sea water also contain sufficient oxygen in solution to support fish life.

Water which has reached a great depth is subjected to enormous pressure and may therefore attain a very high temperature whilst still remaining liquid. As we have seen, a higher temperature enables the

water to take up more solid matter into solution and become super-saturated. Under the action of upheavals caused by the cooling and contraction of the earth's crust these conditions have in some cases become changed, and the excess of solute deposited or "precipitated" as solid matter. Some of the building limestones, the magnesian limestones and dolomites, owe their formation to such action; the stalactites and stalagmites in the well-known limestone caverns are examples of limestone (calcium carbonate) formed by the evaporation of water in which it was formerly dissolved.

The solvent action of water will be more fully discussed in Volume II, under "Natural Waters," but we give here the method of determining the quantity of any solute which is held in solution at different temperatures.

The "solubility" of a substance is taken to be the maximum weight (gms.) of the substance which can be dissolved in 100 gms. of solvent at a given temperature.

**EXPERIMENT 80.**—To find the solubility of common salt at known temperatures.

Place in a small flask a small quantity, say 50 c.cm., of distilled water, add the salt and shake vigorously. If it all dissolves add more and repeat the shaking until the solution is saturated. Stand the flask aside to enable the surplus to settle, and then introduce a thermometer to read the temperature of the solution. Now, with a pipette, withdraw about 10 c.cm. of clear solution and put it into a clean evaporating dish that has previously been weighed. Weigh the dish and solution, so finding by subtraction the weight of the solution. Next evaporate the solvent by heating the dish gently on a sand bath over a Bunsen, continuing until the residue is perfectly dry; this is known by weighing at intervals until no further decrease in weight is shown. Again by subtraction find the weight of the residue.

Weight of dish	= 22.63 gm.
" " " and solution	= 31.83 gm.
" " solution = 31.83 - 22.63	= 9.2 gm.
" " dish and residue	= 25.05 gm.
" " residue = 25.05 - 22.63	= 2.42 gm.
Temperature of solution	= 15.3 deg. Cent.
Therefore weight of salt that would dissolve in 100 gm. of water	
$\frac{2.42 \times 100}{9.2 - 2.42}$	= 35.69 gm.

Repeat the experiment at other temperatures between 0 deg. and 100 deg. and plot the results as a graph. Experimental figures are as follows :—

Temp. Cent.	Solubility	Temp. Cent.	Solubility
0.4	35.77	62.0	37.30
15.3	35.69	75.1	37.80
30.0	36.19	90.0	38.51
45.1	36.58	100.0	39.10



The solubility curve is shown in the graph, Fig. 93, along with curves for various other substances, and it will be seen that, as we have said in Chapter I, common salt or sodium chloride is an exception to the general rule that solubility increases rapidly with increase in temperature.

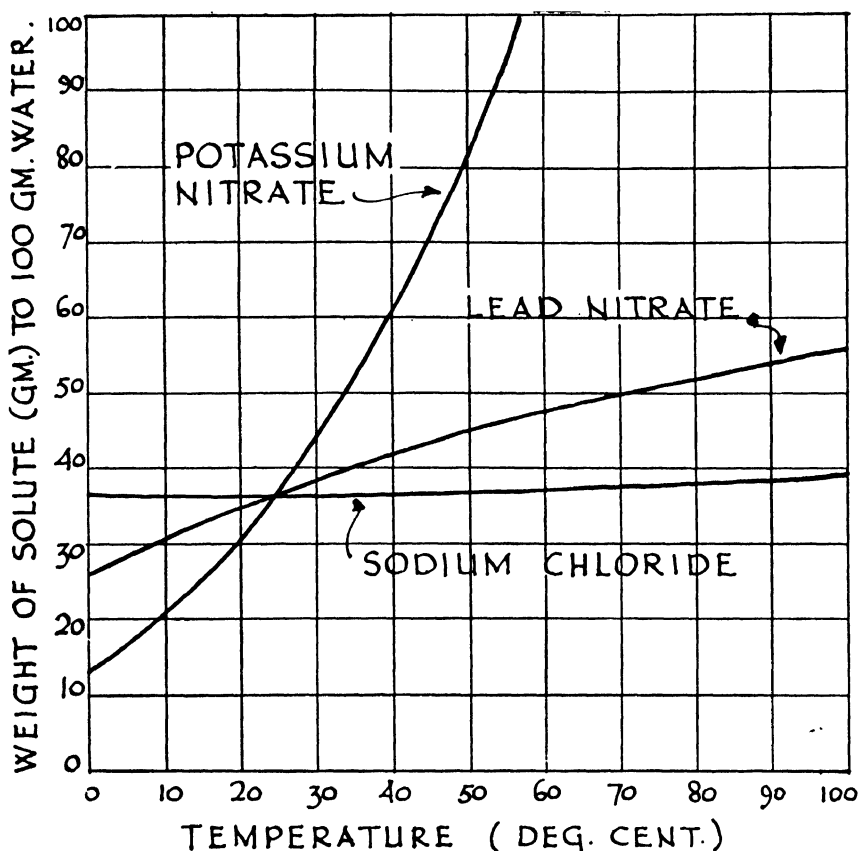


FIG. 93.—Solubility Curves.

#### 4. DISTILLATION.

If a solid-liquid solution is boiled the solvent vaporizes whilst the solute remains. If the vapour is cooled it liquifies or condenses and is now a pure liquid. This process is called distillation.

The apparatus used for laboratory distillation comprises the distilling flask and the Liebig condenser. The distilling flask, shown in Fig. 94, has an outlet tube at the side of the neck, slanted downwards at an angle so as to fit directly into the receiving end of the condenser. The condenser is a long glass tube surrounded by a wider tube with low inlet and high outlet tubes. The space between the two long tubes acts as a jacket

containing cold water which is constantly replaced, so maintaining the constant low temperature necessary for complete condensation.

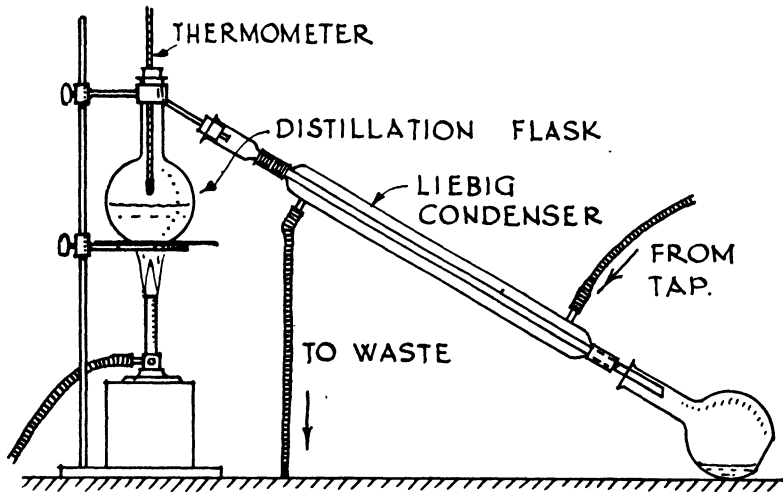


FIG. 94.—Laboratory Distillation Apparatus.

A simpler, though not quite so efficient, arrangement is shown in Fig. 95 in which the distilling flask is replaced by an ordinary flask with two-hole bung, and the condenser by a plain glass tube cooled by wet cloth or blotting paper and the receiving flask itself cooled by a jet of cold water from the tap.

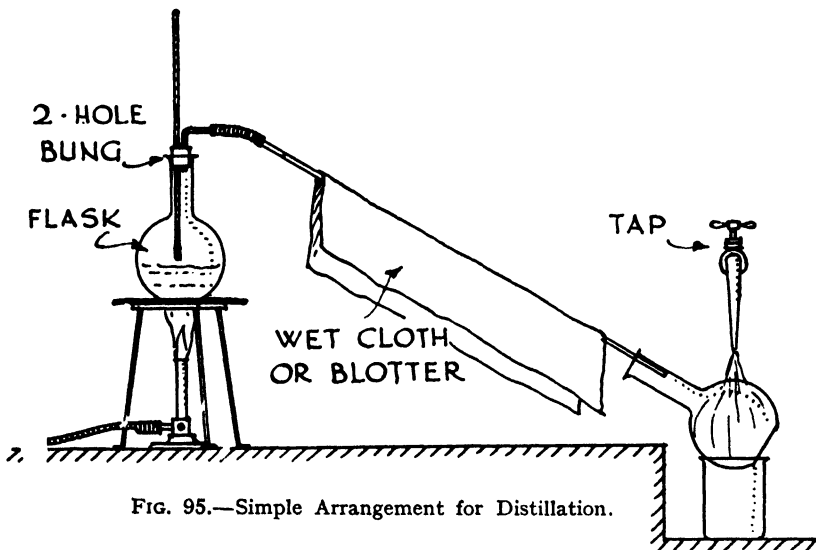


FIG. 95.—Simple Arrangement for Distillation.

The condensed vapour is called the *distillate* and the first few drops to condense may contain impurities from the various glass surfaces. It may therefore be necessary to discard it.

**EXPERIMENT 81.**—To distil a solution of common salt.

Fit up either apparatus, placing the salt solution in the flask (use distilled water) and adjusting the thermometer so that its bulb is clear of the liquid. Boil the solution and collect the distillate as described. If tasted it may be found that a very little salt is still present; this is due to the bubbles of solution in the distilling flask bursting and the spray being carried over along with the water vapour. To be certain of obtaining a really pure distillate it should therefore be re-distilled.

**FRACTIONAL DISTILLATION.**—Liquid solutions may also be separated by distillation if the boiling temperatures of the different liquids are not too near to each other. The solution is first maintained at a temperature just sufficient to vaporize completely the liquid having the lower boiling point but insufficient so to affect the other liquid. This vapour therefore passes over and condenses leaving the second liquid in the distillation flask.

This process is called “fractional distillation” because only a portion of the solution is distilled. The solution may be a mixture of more than two liquids, in which case the process is subsequently repeated at a temperature slightly higher than the boiling point of the next liquid in order, and so on. If the various distillates are required to be absolutely pure it is necessary to re-distil, as a small quantity of the vapours of the other liquids cannot be excluded, especially if they are of a kind which vaporizes easily, such as spirit.

**EXPERIMENT 82.**—To separate a mixture of alcohol and water.

Fit up the apparatus, placing in the distilling flask a mixture of, say, 50 c.cm. of alcohol and 50 c.cm. of distilled water. There is a difference of 20 deg. Cent. between the two boiling points so that the solution may be maintained at just over 80 deg. When distillation is complete test the specific gravity of the distillate and ascertain the percentage of water that has been distilled over. This may be found from the graph, Fig. 96. To isolate the alcohol completely it must be re-distilled.

TABLE 6.

Percentage of alcohol by volume	40	50	60	70	80	90	100
S.G. of mixture . . . . .	.952	.934	.914	.890	.864	.834	.794

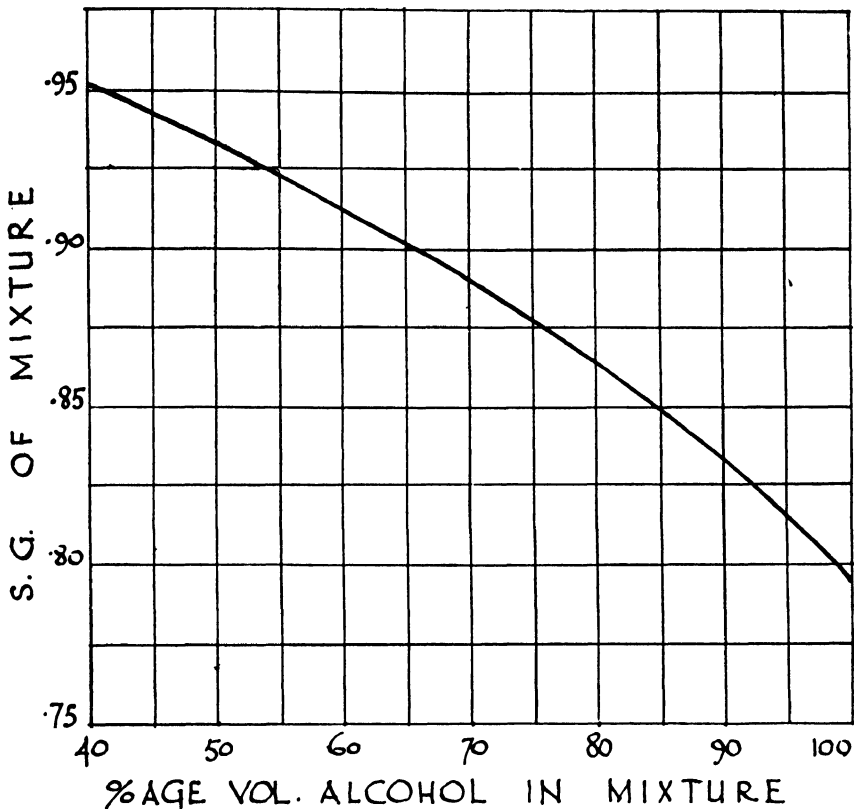


FIG. 96.—Variation in S.G. of Alcohol-Water mixtures.

Strong alcohol or spirits is distilled in this manner from solutions containing little alcohol, *e.g.* from wines or fermented barley, etc.

**DESTRUCTIVE DISTILLATION.**—Crude oil (petroleum) may be refined by fractional distillation, so producing, in order of distilling over, petrol, paraffin oil, gas oil and fuel oil. Industrially, however, the petroleum is distilled by vaporizing the whole at once and permitting the constituents to condense separately as cooling continues. The process is termed "destructive distillation." The crude oil is strongly heated by passing it under pressure through pipes which are arranged in coils inside a furnace. Being under pressure it reaches a high temperature without actually boiling. It is then released into the base of a tower in the form of a vertical cylinder divided into storeys, each storey being a kind of tray communicating with those above and below by pipes arranged to trap the condensed liquid whilst leaving free access for the vapour itself. On release from the end of the heating pipe the pressure is reduced and the hot petroleum immediately vaporizes, the whole of it at once. The

vapour of the constituent having the lowest boiling point rises up the tower from storey to storey to the top ; that having the highest boiling point condenses rapidly and is collected as liquid in the lower storeys. " Intermediate " constituents condense and are collected on intermediate storeys. The distillate from each storey is withdrawn by outlet pipes as required, heavy fuel oil from the lowest storey, the lighter gas oil from those immediately above, the still lighter gas oil from higher ones, and from the top petrol vapour is led by a pipe to a further cooling plant where it, too, condenses. These individual distillates are each further treated by refining, the heaviest fuel oil for instance yielding lubricating oil, paraffin wax and petroleum pitch (see page 7), in order of " lightness "

The production of coal gas, ammonia and tar is effected by the destructive distillation of coal in retorts, the residue being coke. The gas tar is further fractionally distilled to produce benzol, carbolic acid, creosote, naphthalene and coal tar pitch.

## 5. DELIQUESCENT AND EFFLORESCENCE.

In Chapter I, page 18, it was shown how some crystalline substances give up water on heating and break down into dry powder, the anhydrous form of the substance. These usually show a tendency to re-absorb water to form crystals once more ; other similar substances exhibit this tendency so strongly as to take up moisture from the atmosphere in sufficient quantity to dissolve in it and so become a strong solution. They are said to be *deliquescent*. Magnesium chloride is a substance which acts in this way, and if stored in an airtight jar will absorb sufficient moisture from the small quantity of air inside the jar to become wet. Calcium chloride is another example and will be remembered as the substance used in Experiment 75 to extract moisture from hydrogen ; it is invariably used in laboratory work for this purpose. Sodium chloride is not so deliquescent as the examples mentioned but most common salt is not pure sodium chloride, containing amongst other things a small proportion of magnesium chloride ; it therefore, as is well known, becomes moist in damp weather and refuses to " pour."

The practical significance of deliquescence is that building material (brickwork, stonework, concrete, etc.) which contains deliquescent matter is always damp, other than in exceptionally dry weather, and this is not only bad from the hygienic standpoint but hastens the processes of decay and disintegration. Sodium sulphate is such a substance, which may be present in the walling material or jointing material, acquired by contact with soil or formed by the chemical action of atmospheric acids which have been absorbed in solution in rain water.

Some crystalline substances are *efflorescent*. This means that they lose some of their water of crystallization by mere exposure to the atmosphere. Sodium carbonate (washing soda) is perhaps the best known example; the large crystals when fresh are clear, like ice, but upon exposure their arrises lose their sharpness and a white powder appears on their surfaces. This is the dry or anhydrous sodium carbonate and if left for a sufficiently long time the whole mass will break down.

In practice the word "efflorescence" is used to denote the salty formation which sometimes appears in patches on walls. It is also given the names of "saltpetre," "whitewash," etc., erroneously of course for saltpetre is a nitrate and whitewash is a carbonate. The efflorescent salts are neither, but usually sulphates and occasionally chlorides. The subject of efflorescence is dealt with in detail in the next volume, but an indication of some of the ways in which it may be caused is given in the next chapter, in order to show how a vexatious practical problem can only be understood and prevented by a scientific approach.

## CHAPTER IX

### ACIDS, BASES, ALKALIES AND SALTS

1. *Acids.*
2. *Bases and Alkalies.*
3. *Salts.*
4. *Efflorescence in Building Materials.*

Under "The Chemistry of Combustion," in Chapter VII, we discovered that a "solution" of carbon dioxide in water is an acid, carbonic acid  $\text{H}_2\text{CO}_3$ . We also saw that a "solution" of sulphur dioxide is an acid, sulphurous acid  $\text{H}_2\text{SO}_3$ . \*Carbon and sulphur are examples of non-metallic elements. All non-metallic oxides which combine with water yield *acids*.

Similarly we found that a "solution" of magnesium oxide is an alkali, magnesium hydroxide  $\text{Mg}(\text{OH})_2$ . If we had repeated the experiment with calcium we should have produced calcium oxide, and this in water gives calcium hydroxide  $\text{Ca}(\text{OH})_2$ , also an alkali. Sodium would have given us sodium hydroxide, and so on. These are examples of metallic elements. All metallic oxides which combine with water yield *alkalies*.

We must now learn more about these two distinct types of compound and their reactions with each other.

#### 1. ACIDS.

The first property of acids which we met with was their action on the indicator litmus.

LITMUS AS AN INDICATOR.—An indicator is a substance which is used to show, by a change of colour, whether a given substance is acid or alkaline, or neither. The commonest indicator is litmus, which is a dye obtained from certain lichens and which is very sensitive to many chemical substances. Its colour is purple but in contact with any acid substance the colour changes to bright red, in contact with alkalies it turns a clear blue, whilst in pure water and other substances which are neither acid nor alkaline its colour remains unchanged. It is used as a solution or, more conveniently, absorbed into blotting paper and then dried.

Although litmus itself is purple, two kinds of litmus paper are used, red and blue, and they are made by adding acid and alkali respectively to litmus solution, subsequently using the resulting liquids as dye for the paper. Either paper may be changed in colour as often as desired by alternate acid and alkali treatment. Thus if, as often happens, a batch

of blue litmus is found to be deteriorating and turning pink by contact with the atmosphere (which often contains weak acids) or by handling, its colour may be restored by exposing it to an alkaline vapour, or dipping into an alkaline solution and then drying it.

**EXPERIMENT 83.**—To note the effect upon litmus of various substances.

- (a) Take a few drops of a non-metallic oxide solution, say sulphuric acid,  $\text{H}_2\text{SO}_4$ , and test it with litmus paper; the blue paper turns red and the red paper remains red.
- (b) Repeat with a metallic oxide solution, say magnesium hydroxide; the red paper turns blue and the blue remains unchanged.
- (c) Repeat once more with a solution of common salt, sodium chloride  $\text{NaCl}$ ; neither the blue nor the red paper is affected.
- (d) Test distilled water with litmus; there is no effect upon either colour.

**PROPERTIES OF ACIDS.**—All acids react with certain metals and give off hydrogen; in Experiment 76 hydrochloric acid was poured on to zinc in order to prepare hydrogen. All acids therefore contain hydrogen.

All acids have a sharp, sour taste; vinegar, lemon juice, etc., are acids. Acids should not be tasted, however, unless known to be harmless. Acids are classed as “weak” and “strong” according to the degree in which they possess acidic properties. Acetic acid is a weak acid, in fact inferior vinegar is acetic acid artificially coloured to represent malt vinegar, and may be consumed with little or no inconvenience. Sulphuric acid, on the other hand, is a strong acid, and if it comes into contact with the skin will cause severe “burns” by destroying the tissue; if swallowed it causes death. Most acids are weak and therefore harmless, but the few best-known ones are extremely strong, hydrochloric acid ( $\text{HCl}$ ), sulphuric acid ( $\text{H}_2\text{SO}_4$ ), and nitric acid ( $\text{HNO}_3$ ). Note that hydrochloric acid contains no oxygen; non-metallic oxides are therefore not the only acids.

Strong and weak acids should not be confused with concentrated and dilute acids. The terms “strong” and “weak” refer to the properties of the acids themselves, “concentrated” and “dilute” refer to the proportion of acid in solution, whether “neat” or diluted with much water.

All acids combine with alkaline substances to produce solutions of “salts” in water.

**ACTION OF ACIDS UPON BUILDING METALS.**—We shall confine our experiments to sulphuric and hydrochloric acids, these being the ones usually present in industrial atmosphere.

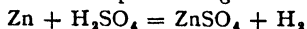
**EXPERIMENT 84.**—The effect of sulphuric acid upon zinc.

Take a little *concentrated* sulphuric acid in a test tube and add a small piece of *granulated* zinc. A few bubbles may appear on the



surface of the zinc, but action is quite feeble. Now heat the test tube, and a pungent gas is given off; this is sulphur dioxide ( $\text{SO}_2$ ).

Next take *dilute* sulphuric acid in the test tube and add zinc. There is a fairly strong action at once, the test tube becomes warm, and the gas given off is found upon testing to be hydrogen.



The hydrogen in the acid has been released and its place taken by the zinc to form zinc sulphate.

**EXPERIMENT 85.**—The effect of sulphuric acid upon copper.

Add a little copper foil to *concentrated* sulphuric acid in a test tube. There is little, if any, action. Heat the tube as in the last experiment, and the same pungent gas is evolved.

Repeat with cold *dilute* acid. There is no apparent action.

**EXPERIMENT 86.**—The effect of sulphuric acid upon iron.

Repeat the experiment using iron filings. The *concentrated* acid has scarcely any effect but on heating, sulphur dioxide is given off.

The *dilute* acid gives an effervescence as in the case of zinc, hydrogen being given off and ferrous sulphate formed.

**EXPERIMENT 87.**—The effect of sulphuric acid upon lead.

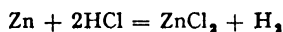
Repeat the experiment using clippings of sheet lead.

The *concentrated* acid has no effect when cold and little when heated.

The *dilute* acid has no effect upon the lead.

**EXPERIMENT 88.**—The effect of hydrochloric acid upon zinc.

Add a small piece of granulated zinc to *concentrated* hydrochloric acid. Vigorous action results, hydrogen being given off and zinc chloride formed.



The action with *dilute* acid is similar (as was seen in Experiment 76) but not so vigorous.

**EXPERIMENT 89.**—The effect of hydrochloric acid upon copper.

Test the effect of *concentrated* hydrochloric acid upon copper foil. There is no action. Heat the mixture and very little action results.

Test again with *dilute* acid. Again there is no action.

**EXPERIMENT 90.**—The effect of hydrochloric acid upon iron.

Add some iron filings to *concentrated* hydrochloric acid in a test tube. Strong action takes place, hydrogen being given off and ferrous chloride formed.

Test again with *dilute* acid and a similar result is obtained.

**EXPERIMENT 91.**—The effect of hydrochloric acid upon lead.

Repeat the experiment with sheet lead. *Concentrated* acid gives no action when cold and very little when heated.

*Dilute* acid has no action whatever.

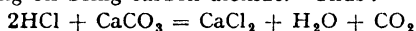
From these experiments we see that for situations exposed to the atmosphere, copper and lead are very superior to zinc and iron, from the viewpoint of acid attack, and we also saw that this superiority extends to their behaviour under the action of oxygen and moisture.

The substances left after the liberation of hydrogen are called salts. These are named by the metal and the acid taking part in the action, for example, salts obtained from sulphuric acid and a metal are *sulphates*, from hydrochloric acid and a metal *chlorides*, from nitric acid and a metal *nitrates*, of the particular metal. As has been stated, salts are also produced when acids react with alkalies, but this question is left to Section 3 of this Chapter.

**ACTION OF ACIDS UPON BUILDING STONES.**—Acids act strongly upon carbonates, releasing carbon dioxide. Limestones are calcium carbonate and, with the exception of magnesian limestones, which contain magnesium carbonate too, are attacked by cold acid. This fact is utilized in a test for the presence of lime in a stone or brick.

**EXPERIMENT 92.**—To test building stones for the presence of lime.

Apply a few drops of dilute hydrochloric acid to specimens of different stones. Any chemical action is indicated by effervescence, the gas coming off being carbon dioxide. Thus :—



The acid must be heated to have any effect upon magnesian limestones.

## 2. BASES AND ALKALIES.

When a metal combines with an acid under normal conditions it gives a salt and hydrogen. A *base* is a substance which combines with an acid, giving a salt and water. Bases must therefore contain oxygen, since water is a compound of hydrogen and oxygen. With the single exception of ammonia all bases are either oxides or hydroxides of metals. (A hydroxide is an oxide dissolved in water so as to combine chemically.) A soluble base is called an *alkali*; calcium hydroxide (slaked lime) and sodium hydroxide (caustic soda) are examples. "Hydrate" is another name for "hydroxide," the well-known hydrated lime is thus merely calcium hydroxide, but slaked by steam so as to ensure perfect slaking.

**PROPERTIES OF ALKALIES.**—All alkalies turn red litmus blue. All alkalies combine with acids to form salts and water. Just as there are weak and strong acids, so alkalies may be classified as weak and strong. Ammonia is a weak alkali, whilst caustic soda is a strong alkali. Just as with strong acids strong alkalies are corrosive and destroy tissue, causing severe "burns." Caustic soda is extremely deliquescent and when exposed to the atmosphere it absorbs moisture and carbon dioxide, turning slowly into washing soda, thus :—



This, we saw, is extremely efflorescent and slowly loses its water of crystallization upon continued exposure, leaving ultimately the anhydrous  $\text{Na}_2\text{CO}_3$ .

The strong alkalies, such as sodium hydroxide and potassium hydroxide, have a peculiar oily feel when rubbed between the fingers.

### 3. SALTS.

A salt has already been explained as the substance produced when an acid and an alkali react. It is a compound in which the hydrogen of an acid is wholly or partly replaced by a metal. At normal temperature salts are crystalline solids.

**FORMATION OF SALTS.**—When an acid and an alkali react to produce a salt they are said to be “neutralized.” The neutralization is only mutual when a certain definite weight of acid and a definite weight of alkali are used. If more acid than this fixed amount is used the excess will remain as acid, and similarly any excess of alkali remains. Since experimental error precludes the possibility of really exact quantities being used it is better to leave a minute excess of acid rather than of alkali, as the acid excess subsequently evaporates more readily than does alkali.

**EXPERIMENT 93.**—To neutralize sodium hydroxide and hydrochloric acid.

Fix a burette in a stand as in Fig. 97 and partly fill it with dilute hydrochloric acid. The burette is used merely to deliver the acid in minute quantities as required; no readings need be taken. Under the burette place an evaporating dish containing a small quantity

of sodium hydroxide. Place a strip of litmus paper in the dish so as to colour the hydroxide slightly; it may then be removed as too much litmus will colour the resulting salt. The hydroxide will then be faintly blue. Add acid by adjusting the burette tap until the colour turns to a faint pink. The mixture is now slightly acid.

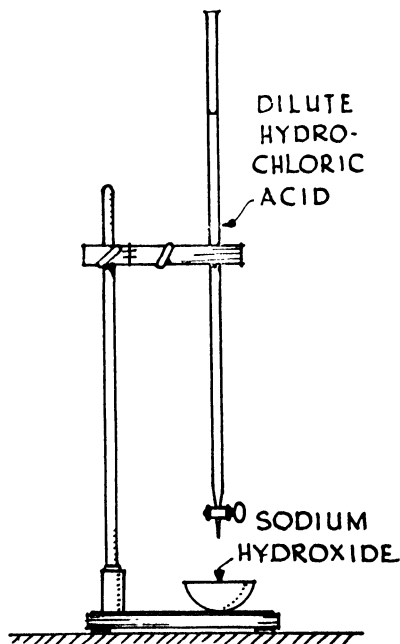
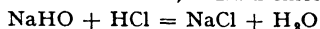


FIG. 97.—Preparation of a Salt by Mutual Neutralization.

At this point add just a little more hydroxide until the blue tint reappears and then add acid drop by drop, stirring all the time until the mixture is neither blue nor pink. This is not easy because of the difficulty of ensuring a uniform mixture by mere stirring, but if either leave a faint trace of blue rather than pink. We now have a solution of salt in water with a trace of acid as excess.

Place the dish on a sand or water bath over a Bunsen and evaporate the water. A white powder will be left as residue, and when cool taste it ; it is common salt, sodium chloride NaCl.



The experiment may possibly be more interesting if we prepare the sodium hydroxide on the spot by putting water into the dish and adding a very small piece of metallic sodium, before adding the acid. We then start the experiment with sodium, hydrochloric acid and water, and end with common salt.

The experiment may be repeated with potassium hydroxide in the dish and dilute nitric acid in the burette. The salt obtained is then potassium nitrate or saltpetre. Similarly calcium hydroxide and dilute sulphuric acid give calcium sulphate, and so on.

#### 4. EFFLORESCENCE IN BUILDING MATERIALS.

Efflorescence is usually very much in evidence on sites near to the sea. The chief cause here, apart from the more usual causes which are in such cases subsidiary only, is sodium chloride. Seashore sand may be used for making mortar, or shingle from the beach may be utilized in the preparation of concrete. Sometimes, indeed, in such works as sea walls, sea water may be employed in the mixing. Such practices are well known to be detrimental, as the salt contained in these materials crystallizes on the face of the work as it dries out. Even if such materials are not used the air, and consequently the rain, in such positions often contains small quantities of the salt which is absorbed in solution by the dry wall and subsequently shows as efflorescence on evaporation of the water at the surface.

The foregoing may be regarded as an exceptional instance. Most efflorescence is composed of sulphates which are not so harmful, though just as unsightly. Calcium and magnesium sulphates are the most usual, but sulphates of potassium and sodium are also met with. These may be contained in the materials themselves, especially in the case of bricks, or more often they are formed subsequently by chemical action. Some brick earths contain calcium carbonate ( $\text{CaCO}_3$ ) which is transformed during firing into calcium oxide ( $\text{CaO}$ ) by the release of carbon dioxide ( $\text{CO}_2$ ). Sulphur dioxide is one of the gases given off into the air as a result of the burning of fuel and in other ways in industrial districts. This is soluble in water and is thus taken into solution by atmospheric

moisture to form sulphurous acid ( $\text{SO}_2 + \text{H}_2\text{O} = \text{H}_2\text{SO}_3$ ). Further oxygen from the atmosphere may combine, so giving sulphuric acid ( $\text{H}_2\text{SO}_4$ ), one of the most destructive agencies to which building materials can be exposed, especially those containing lime in any form. Rain containing sulphuric acid is thus absorbed into the brickwork, etc., where it reacts with the calcium oxide to form calcium sulphate and water ( $\text{CaO} + \text{H}_2\text{SO}_4 = \text{CaSO}_4 + \text{H}_2\text{O}$ ). The sulphate remains in solution inside the material until, in the drying out process, it is drawn to the surface where the solvent, water, evaporates leaving the solute, calcium sulphate, to crystallize and so form the efflorescence.

As stated, other salts may also form part of the deposit. In one case an important building in course of erection was unusually badly marred by efflorescence. The trouble appeared to have originated in the bricks themselves, or in the mortar which was being used. A sample of the powder was analysed and found to consist mainly of calcium sulphate and a fair proportion of magnesium sulphate, together with very much smaller quantities of three other salts. As a result of experiments on a number of unused bricks all were found to contain the same salts in almost identical proportions.

In a very porous material the crystallization may occur in the pores themselves near the surface as well as at the surface. The expansion of the pores caused by the "growth" of the crystals thus starts disruption of the particles of the material, constituting severe weathering which after repeated occurrence means decay.

The disruptive effect of this crystal growth is more evident when it occurs on the internal face of a wall such as when a new building is overheated in an attempt to dry out the walls quickly. It usually forms on the surface of the plaster, in the thickness of distemper or water paint, ruining this by breaking it up into flakes and powder. Under wallpaper it speedily pushes the paper away from contact with the plaster, and even in some cases thrusts plaster away from brickwork.

The part played by efflorescence in the disintegration and decay of walling materials is only one, and by no means the most important. It is therefore more fully discussed in conjunction with other destructive agencies in a subsequent volume.

## CARBON AND CARBON COMPOUNDS

1. *Carbon.*
2. *Oxides of Carbon.*
3. *Carbonates.*

**1. CARBON.**

Carbon is a non-metallic element which occurs in nature in two forms, graphite and diamond. Both are pure carbon in crystalline form. Charcoal is an artificial form of pure carbon, and is amorphous.

Graphite is found in nature in the form of hexagonal crystals, and can also be produced artificially by passing a strong electric current through powdered coke. It is the soft grey-black solid used for making "lead" pencils. Its chief use is as a lubricant because of the ease with which the molecules separate in definite parallel planes. It resists chemical action and is therefore used in the making of linings for vessels in the chemical industry. Its melting point is very much higher than those of other substances and so it is used, mixed with fireclay, for crucibles, kiln linings, etc.

Diamond is found as octahedral crystals of carbon. Its appearance is well known and is as unlike that of graphite as it could be. Apart from its value as a gem it is used industrially in the cutting of hard substances, granite and other stones for instance, owing to its intense hardness. The steel saws used for such a purpose have small steel inserts at intervals, each set with a small diamond projecting clear of the general surface.

Both graphite and diamond, if heated strongly enough, give off the same quantity of carbon dioxide gas and leave no residue. This proves that they both consist of pure carbon only; the physical difference in the shape of their crystals is the only real difference between them.

Charcoal is an artificial form of pure carbon, not crystalline like diamond and graphite. It is the residue left after heating organic substances, which contain carbon compounds, out of contact with air. The purest form of charcoal is obtained in this way from sugar. It is very porous, its bulk specific gravity being only  $\cdot 2$ , but its solid specific gravity is  $1\cdot 9$ , almost identical to that of graphite. The specific gravity of diamond is  $3\cdot 52$ . Charcoal has very strong adsorbent properties, especially for gases, taking up from 100 to 200 times its own volume of gas. It is therefore used as the principal adsorbent in respirators. It also adsorbs dyes from solution and so finds many industrial uses in refining, etc. It combines with metallic oxides, under strong heat, leaving metals,

as was shown in Experiment 57, page 113, and is thus used in the extraction of metals from their ores. Impure forms of charcoal include bone and wood charcoal, coke, soot and coal. Coal is destructively distilled as already described, the residue being coke.

## 2. OXIDES OF CARBON.

Carbon combines with oxygen under different conditions to produce carbon monoxide, CO, and carbon dioxide, CO<sub>2</sub>. Both are gases and are of great importance.

**Carbon Monoxide.**—This is formed in coal or coke fires where a limited supply of air has access to the red hot fuel, such as in “combustion” stoves. First the atmospheric oxygen combines with the carbon to form carbon dioxide ( $C + O_2 = CO_2$ ). This lasts only momentarily, and further reaction with the red hot carbon results in what amounts to a partial reduction,  $CO_2 + C = 2CO$ . This carbon monoxide passes from the top of the burning fuel and if allowed to accumulate in an enclosed space such as an unventilated room its poisonous properties may cause fatalities. Such are indeed fairly common when coke is burned in a brazier in places like cellars or “dug-outs.” It is therefore most important that any coke-burning apparatus should have an efficient flue discharging into the open air. If such is the case the carbon monoxide is dispersed and does no harm, but if a brazier is used in the open air the monoxide issuing from the burning fuel combines with oxygen again to form carbon dioxide,  $2CO + O_2 = 2CO_2$ .

**PROPERTIES OF CARBON MONOXIDE.**—Carbon monoxide is a slightly soluble gas, colourless and almost odourless; its action upon animal life is thus insidious, as if it had a definite odour like coal gas its victims would have some warning. It combines with the red matter of the blood and is so conveyed to all parts of the body in place of the oxygen which is normally so carried. Its density is about the same as that of air, so that it diffuses very easily indoors. It burns, but does not support combustion, and combines chemically with some elements. We have seen that it combines with oxygen to form carbon dioxide which is not so dangerous; it also combines readily with chlorine, itself poisonous, to form phosgene, a much more deadly gas. Thus  $CO + Cl_2 = COCl_2$ .

Carbon monoxide poisoning is caused, always in ill-ventilated places, not only by fumes from coke stoves but also from coal gas burners such as are used in cookers, geysers, etc., and also from car exhaust pipes when the engine is running slowly. The exhaust gases from the engine, when running at normal speeds, include carbon dioxide; when, however, the engine is turning over slowly such as in “warming up” insufficient air is contained in the explosive mixture to ensure good combustion and

carbon monoxide is formed instead of dioxide. As such a state of affairs invariably occurs indoors, before driving away, the high number of fatalities from this cause is explained.

**INDUSTRIAL FUEL GASES.**—Let us reconsider the coke stove mentioned earlier. The gas issuing from the top of the fire is carbon monoxide which normally burns there in combination with oxygen admitted at this point, carbon dioxide being produced and escaping via the flue. If no oxygen were admitted here the carbon monoxide itself would pass up the flue, together with the atmospheric nitrogen which entered as part of the air at the bottom of the stove, and which has not been changed in passing through the fire. This mixture might be collected at the flue outlet and burned as a fuel, the carbon monoxide being the combustible constituent.

Such a mixture is in fact manufactured for use as a fuel, alternative to coal gas, and is known as "producer gas." It is produced commercially by drawing a stream of air through burning coke or charcoal, and in some districts is "laid on" to premises by mains and pipes, or in large concerns is produced for individual use.

Another industrial fuel is called "water gas." This is produced by blowing a jet of steam through burning coke, thus :— $\text{H}_2\text{O} + \text{C} = \text{CO} + \text{H}_2$ . This gas therefore contains an equal volume of hydrogen and is thus more efficient as a fuel. Modification of the process results in gases composed of producer and water gases in various proportions, these sometimes receiving proprietary names. Most of these gases, prepared commercially, contain a small percentage of other gases such as sulphur compounds derived from impurities in the coke, but it is the carbon monoxide or the carbon monoxide and hydrogen together which gives them their value as fuels.

**Carbon Dioxide.**—We have already encountered carbon dioxide, and this is the more usual combination of carbon and oxygen. It is evolved from all forms of oxidation including combustion, decay and respiration, so that a constant stream of it is continually being released into the atmosphere. Fortunately all plants (except fungi and mould growths) assimilate this gas under the action of light, and convert it into the starch, sugar, etc. necessary for their life and growth. Nature thus strikes such a happy balance that the proportion of carbon dioxide in the atmosphere remains fairly constant.

**PROPERTIES OF CARBON DIOXIDE.**—Carbon dioxide is colourless and almost odourless. It is not actually poisonous but can cause death by excluding oxygen, so producing suffocation. This, together with the fact that its density is half as much again as that of air, renders it liable to collect in low, unventilated spaces such as cellars, wells, disused mine



workings, etc. In such cases it usually originates from the decay of organic matter in the soil, and in lime kilns it is a product of the burning of the limestone. It is only slightly soluble in water at ordinary temperatures and pressures, but upon increasing the pressure it goes into solution very readily, and this is taken advantage of in the preparation of aerated waters. It does not burn, since it already contains the maximum possible of oxygen, and owing to its consequent stability it does not support combustion, except that of the metals sodium, magnesium, etc. These exceptional substances, when they burn in carbon dioxide, evolve terrific heat, greater than that given out by carbon when burning. They thus have the peculiar property of taking up the oxygen from the carbon dioxide and leaving carbon. Carbon dioxide is used in certain types of fire extinguisher for oil fires; the apparatus is arranged to generate a foam of carbon dioxide bubbles which spreads over the surface of the blazing oil and extinguishes the flames by denying the access of oxygen.

Just as natural water contains oxygen in solution, necessary to fish life, so it sustains plant life by reason of the carbon dioxide also dissolved in it. As in the air, so in water, animal respiration requires oxygen and replaces it with carbon dioxide; plant life, in the light, absorbs carbon dioxide and gives out oxygen, so maintaining a balance. When carbon dioxide dissolves in water part of it combines with the water to form carbonic acid, a very weak acid which, however, possesses all the acidic properties such as affecting litmus, combining with alkalies to form salts, etc.

Carbon dioxide in natural water causes "temporary hardness" by permitting the solution of limestone. On boiling the water the gas is released and the previously dissolved substances are deposited as solid matter, hence the "furr" in kettles, pipes and boilers.

As will be seen in the following section, all carbonates contain carbon dioxide, and the action of the gas on calcium hydroxide forms the chief test for recognizing carbon dioxide. In Experiment 64, page 120, we identified the gas by adding lime water which thereupon turned milky or cloudy, by the formation of a cloud of particles of calcium carbonate.

**EXPERIMENT 94.**—To show that carbon dioxide is evolved in combustion.

Ignite a wood splint and thrust it slowly into a test tube held vertically. When it is extinguished pour in a little lime water, place the thumb over the mouth of the tube, and shake well. The lime water turns milky, proving the presence of carbon dioxide.

**EXPERIMENT 95.**—To show that carbon dioxide is evolved in respiration.

Fit a small flask with two glass tubes as shown in Fig. 98 after placing some lime water in the flask. Applying the mouth to A draw air through B. It bubbles through the lime water without visible effect, showing that the atmosphere contains little carbon dioxide. Next apply the mouth to B and exhale through the lime water; this time it turns milky in a very short time.

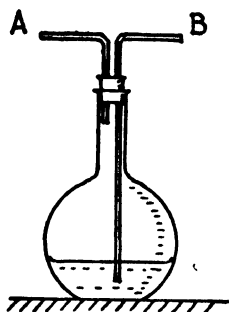


FIG. 98.  
Carbon Dioxide evolved  
in Respiration.

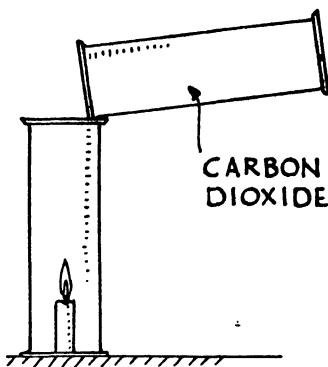


FIG. 99.—To Show the Low  
Density of Carbon Dioxide.

**EXPERIMENT 96.**—To show that carbon dioxide is denser than air, and that it does not support combustion.

Prepare a jar full of carbon dioxide and cover it with a ground glass plate until required. Light a short wax candle in the bottom of another gas jar and observe that it has little difficulty in burning. Now take the full jar and, in a draught-free position, remove the plate and apply the jar to the jar containing the burning candle as though to pour from one to the other. The candle is extinguished, showing that we have actually poured the gas from one jar into the other.

### 3. CARBONATES.

Carbon dioxide is a non-metallic oxide, soluble in water, and thus forms an acid which we have learnt is carbonic acid. On page 143 we gave some of the commoner salts, produced by the exchange of a metal for the hydrogen of an acid, sulphates from sulphuric acid, nitrates from nitric acid, etc. The salt resulting from the action of carbonic acid is called a *carbonate*, but carbonic acid is too weak to combine with the insoluble bases.

**EXPERIMENT 97.**—To show the action of carbon dioxide on sodium hydroxide.

Carbon dioxide is most conveniently prepared in the laboratory by the action of hydrochloric acid on marble or limestone chips. The reaction is :—



The chips are placed in a Woulff's bottle as in Fig. 100, covered with water, and the acid added through a thistle funnel. Carbon dioxide is given off and calcium chloride and water left in the bottle. The carbon dioxide is led by a tube to a beaker containing the sodium hydroxide and allowed to bubble through it. Sodium carbonate (washing soda) and water are produced :—



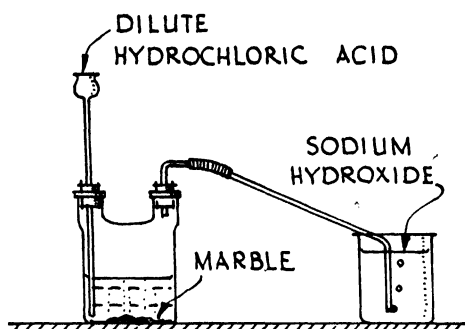
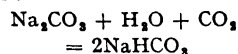


FIG. 100.—Action of Carbon Dioxide upon Sodium Hydroxide.

If we continue to pass the carbon dioxide through, the carbonate changes to sodium bicarbonate thus :—



Atmospheric carbonic acid reacts with copper to form a carbonate at the same time that atmospheric oxygen forms the hydroxide of copper (see page 111). The green protective coating which forms on copper when

used outside is therefore a “basic carbonate,”  $\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$ .

The principal carbonate is calcium carbonate, existing widely in nature as chalk, marble and other forms of limestone, also as the cementing agent in some sandstones, and in shells and bones of animal life. We saw in Experiment 92 that calcium carbonate readily yields calcium chloride, water and carbon dioxide by the addition of hydrochloric acid. Sulphuric acid similarly produces calcium sulphate, water and carbon dioxide.

The setting of lime plaster, unless “gauged” with other materials, is a process of carbonation. The slaked lime (calcium hydroxide) takes up atmospheric carbon dioxide to form crystalline calcium carbonate. The process is an exceedingly lengthy one and this is the reason for the addition of other materials to reduce the setting time.

## CHAPTER XI

### LIME AND PLASTER

1. *Calcination of Limestone.*
2. *Slaking and Setting of Lime.*
3. *Preparation and Setting of Plaster.*
4. *Gypsum Cements.*

#### 1. CALCINATION OF LIMESTONE.

Limestones consist mainly of calcium carbonate, which in some cases is composed of the calcareous remains of marine life deposited on the bed of the ocean, and subsequently raised by upheaval. Chalk has been formed in this way. Other limestones are precipitated from solution, as has been already mentioned, whilst others consist of sand grains deposited from running water on to the ocean shelf at the same time as marine remains; they are thus composed of sand cemented with lime.

The purest form of calcium carbonate is eggshell, oyster shell and similar substances, but chalk is almost as pure, and as it is available in quantity it is used when a pure or "fat" lime is required.

Quicklime is calcium oxide and, as we have seen, it can be obtained by the combustion of calcium in oxygen. This cannot, however, be done on a commercial scale; it is cheaper and simpler to obtain it from the carbonate. This is done by calcination or heating the carbonate to a red heat, so driving off first the moisture and then releasing carbon dioxide:— $\text{CaCO}_3 = \text{CaO} + \text{CO}_2$ .

**EXPERIMENT 98.**—To prepare quicklime from calcium carbonate.

Place some powdered chalk or crushed marble in a small crucible or fireproof basin supported on a pipeclay triangle on a tripod. Heat it strongly by a Meker burner so that it remains at red heat for some hours. An ordinary Bunsen is unlikely to provide a sufficiently high temperature. If a furnace is available calcination

will not take so long. Then leave it to cool in a desiccator. Quicklime is highly deliquescent and would absorb atmospheric moisture if left to cool in air. A desiccator is a glass vessel containing calcium chloride or sulphuric acid, which absorbs any

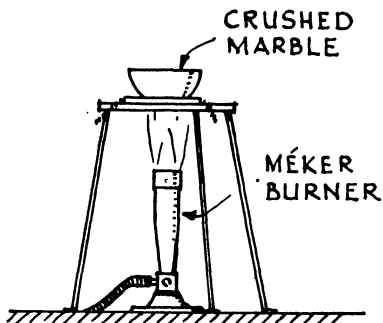


FIG. 101.—Preparation of Quicklime.

moisture and so keeps the air in the vessel dry. The crucible is placed on a grid in the upper part of the vessel and an airtight lid placed on top. Leave the quicklime for a subsequent experiment. We can prove that carbon dioxide is lost during calcination by the method given in the next experiment.

**EXPERIMENT 99.**—To show that calcination of chalk releases carbon dioxide.

Place a little powdered marble or chalk in a hard glass combustion tube supported as in Fig. 102. From one end lead a narrow glass tube to the bottom of a beaker containing lime water. To the other end fit a rubber tube leading from an aspirator. Apply a spread flame to the marble so as to heat it to redness. As the water level in the aspirator rises, air passes through the combustion tube and carbon dioxide given off is forced through the lime water, causing it to turn milky.

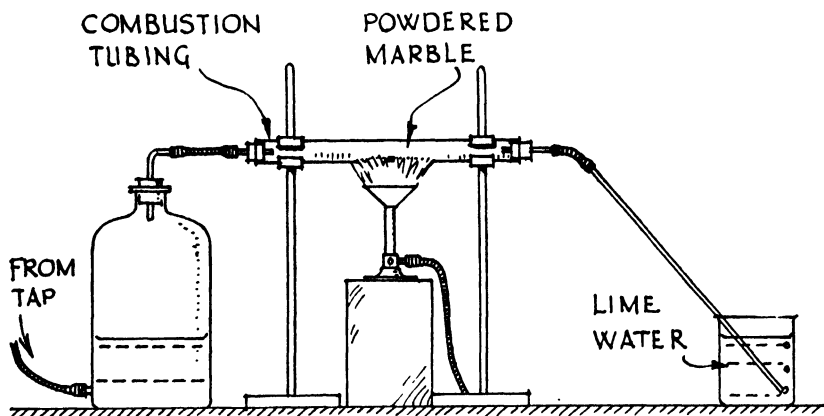


FIG. 102.—Carbon Dioxide produced by Calcination of Chalk.

Quicklime is prepared on a commercial scale by “burning” the limestone in kilns. The traditional type of kiln, still in use in many parts, is a roughly built chamber, open at the top and built in to the side of a bank or cliff. At the bottom is a fire opening with access door, and over it is a roughly built vault with open joints through which the flames and hot gases can pass. This is generally built at each burning operation out of the larger lumps of limestone. Over this the remainder of the space is filled loosely with the limestone to be burnt, and the fire started at the base. Calcination takes several days, and after cooling the kiln is emptied from the bottom. The process is thus intermittent and the burning far from uniform, the stone at the top being underburnt if the remainder is correctly burnt.

In another type of kiln burning is continuous, but this advantage is obtained at the expense of the purity of the finished quicklime. The

fuel has to be mixed with the stone and fed into the kiln at the top as the level is lowered by the withdrawal of quicklime from the bottom. The refuse from the fuel is thus mixed with the lime itself and cannot be removed entirely.

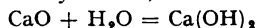
The more modern concerns employ scientifically designed kilns in which, whilst the process is continuous, the fuel is burnt separately and the heated gases only pass through the stone.

The processes described apply to all types of limestone which are used for burning, but the quicklime itself has different properties according to the type of stone. In this elementary explanation we have assumed a fairly pure limestone which yields a pure or "fat" lime such as that used for plastering. Other kinds of limestone contain matter other than calcium carbonate, these sometimes being of such a nature as drastically to revise the subsequent chemical process of setting.

## 2. SLAKING AND SETTING OF LIME.

EXPERIMENT 100.—To observe the action of water upon quicklime.

Remove from the desiccator the quicklime prepared in Experiment 98 and, by means of a pipette, add to it a few drops of water. The water disappears and the surface of the lime cracks and lifts, whilst steam is given off and the crucible becomes hot, all signs of very strong chemical action. The quicklime has been converted into slaked lime, calcium hydroxide, thus :—



The process is also called hydration and if the slaked lime is made red hot it loses steam and is re-converted into quicklime; this is de-hydration. Touch the slaked lime with a piece of moistened litmus paper. It turns blue, showing the alkaline nature of the slaked lime.

In practice the slaking of "fat" lime is carried out in large tubs or in pits dug out on the site. A considerable amount of water is added until the lime has about the consistency of cream. After a time the surplus water remains on top as a clear liquid, so protecting the "lime putty" beneath from dirt and from drying up. This putty is the "fine stuff" used with a proportion of sand by the plasterer for the finishing coat of plaster to walls, ceilings, etc., and it has to mature for a considerable period before use, both to ensure thorough slaking and to develop "workability."

For the previous coats of plaster the lime has to be slaked with just the correct amount of water to form what is called a "dry hydrate." If too little is used it is said to be "hot" or "burnt" and there is a danger of unslaked particles being mixed up in the plaster and applied to the walls, where it slakes slowly at a later date and blisters the surfaces.

It has been found that lime putty is more easy to "work" than a dry hydrate which is subsequently made into putty by the addition of water.

### Setting of Lime.—

**EXPERIMENT 101.**—To demonstrate the carbonation of slaked lime.

Take the slaked lime from Experiment 100 and with a gauging trowel (shown in Fig. 103) make it up into a stiff paste. If necessary add a little more water until slaking appears to be complete. Strike and smooth the paste into two thin pats each on a small square of plate glass. Place these on a glass-topped table and cover each with a bell jar or receiver greased on its ground edge so that an airtight joint is made. Before covering the second pat place beside it an evaporating dish containing marble chippings and a little very dilute hydrochloric acid. After a couple of weeks lift the receivers and inspect the specimens. Both will have developed a more or less hard skin due to evaporation of surplus water. Break open both pats and compare their consistency. The first will be found to be much softer than the second. Test both by pouring on a few drops of hydrochloric acid. The first may show a very slight effervescence, but the action in the second case will be violent by comparison.

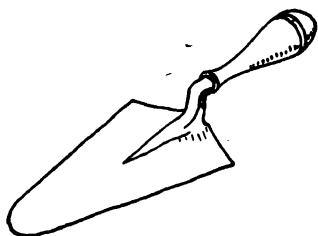


FIG. 103.—Gauging Trowel.

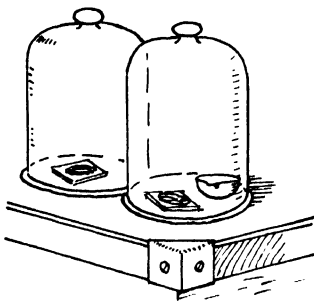


FIG. 104.—Carbonation of Slaked Lime.

This is the action which takes place when fat lime sets in air, the carbon dioxide from the atmosphere combining with the slaked lime to produce a crystalline form of calcium carbonate. The action is really the reverse of the calcining and slaking processes, thus:  $\text{Ca(OH)}_2 + \text{CO}_2 = \text{CaCO}_3 \cdot \text{H}_2\text{O}$ , but is obviously a very lengthy process. From practical considerations, therefore, it is usual to encourage earlier setting by the addition of a small proportion of other material, usually plaster of Paris. The sand in lime plaster (generally 3 of sand to 1 of lime) is used merely as a filler, although it helps air to penetrate, so assisting carbonation, and also restrains the drying shrinkage of the lime.

**LEAN LIMES.**—Limes other than fat limes are calcined from limestones which contain appreciable proportions of substances other than

calcium carbonate. They are classed as "lean" limes and "hydraulic" limes, but there is no hard and fast dividing line.

Lean limes may be obtained from the type of stone called "grey chalk" or "grey stone," and the impurities do not as a rule improve the properties of the lime in any way; they merely act like a filler such as sand. The burning of grey limestone calls for greater care than that of pure limestone because if overburnt the impurities combine with the lime and make it more difficult to slake. Apart from this the burning, slaking and setting of lean limes are exactly as for fat limes, but they do not slake so readily. They ought really to be considered as inferior kinds of fat lime.

**HYDRAULIC LIMES.**—These also contain impurities but they are of such a nature as to improve the properties of the lime. The best known is prepared from "blue lias" limestone. They slake very slowly, and setting is not by carbonation as in the other cases but is due to complicated reactions rather like those taking place in the setting of Portland cement. They are called "hydraulic" because of their power of setting under water. The hydraulic limes differ in their degree of hydraulicity, and are commonly classed as "feebly," "moderately" and "eminently" hydraulic. They are the only limes that should be used for mortar and concrete, but nowadays appear to be losing popularity in favour of Portland cement. Like lean limes they are adversely affected by overburning, and it is perhaps the greater reliability of Portland cement which, together with its definitely known properties, is causing it to supplant lime.

### 3. PREPARATION AND SETTING OF PLASTER.

Although lime (calcium hydrate) is used in plastering, the word "plaster" is usually reserved for calcium sulphate, which is quite distinct, as will have been appreciated from Chapter VIII. Calcium sulphate is found in nature as the crystalline "gypsum" or "spar," in the N. and E. Midland districts of this country. It is also common in many other countries, notably in France around Paris, hence the name, "plaster of Paris," given to the pure finished product.

Pure gypsum is calcium sulphate, each molecule of which has two molecules of water of crystallization,  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ . It is crushed and heated in metal pans until some of the water of crystallization is driven off as steam, leaving the fine white powder, plaster. The amount of water driven off during this process has a great bearing upon the subsequent behaviour of the plaster. For a "hemi-hydrate" plaster three-quarters of the water is removed in the "boiling" process, thus:— $2(\text{CaSO}_4 \cdot 2\text{H}_2\text{O}) = (2\text{CaSO}_4)_2\text{H}_2\text{O} + 3\text{H}_2\text{O}$ . The temperature maintained for this result is approximately 130 deg. Cent.



If "boiling" is carried out at a higher temperature than about 200 deg. the whole of the water is driven off, leaving the anhydrous calcium sulphate  $\text{CaSO}_4$ . This is known as "hard-burnt" or "dead-burnt" plaster, and is similar to the natural "anhydrite."

**EXPERIMENT 102.**—To prepare gypsum plaster.

Powder some gypsum in a mortar, place it in an evaporating dish on an asbestos gauze supported on a tripod, and heat cautiously with a Bunsen. The "boiling" action described soon commences and the powder is stirred constantly, the temperature not being allowed to rise higher than 130 deg. C. (an ordinary 100 deg. thermometer must clearly not be used, but one reading up to 300 or 400 deg.). When the action ceases remove the Bunsen and allow the dish to cool. This is "hemi-hydrate" plaster.

Repeat the experiment with another batch of gypsum, but this time at a higher temperature. When action has ceased place this dish to cool in a desiccator. Keep the two dishes of plaster for a subsequent experiment on setting.

**Setting of Plaster.**—When the hemi-hydrate plaster is mixed up with water it sets hard in a few minutes. The water combines with the plaster to form gypsum again; it is thus a reversal of the boiling process.

For plastering the setting is much too rapid, and a "retarder" is therefore necessary. This may be a substance added during manufacture or added to the water used in the mixing. The substance must be such as will partially obstruct the formation of crystals which constitutes the setting process, and for this purpose some form of colloid is used. Incidentally, and contrary to what might be expected, provided that retarder is not added in too great a proportion, the mechanical strength of the set plaster is increased, but if too much is used the strength is reduced.

Hard-burnt plaster is very much slower in setting than hemi-hydrate plaster, because of the different crystal structure, but ultimately develops greater strength. In order to speed up the setting, "accelerators" are added during manufacture, such as alum or lime.

**EXPERIMENT 103.**—To observe the setting of plaster of Paris.

Take a convenient amount, say 10 gm., 20 gm., etc., of the hemi-hydrate prepared in Experiment 102 and a measured volume of water in a graduated cylinder. Add water slowly to the plaster on a glass plate, mixing with a gauging trowel until a workable paste is produced. Note the volume of water used, and at the rate of 1 gm. per c.cm., calculate the percentage by weight. Note the exact time at which the water is first added, and also when the plaster has set. The difference is the setting time and will be found to be 5 or 6 minutes only. Place the bulb of a thermometer in the pat during setting and note the rise in temperature, due to the giving up of latent heat during crystallization. The thermometer should be withdrawn before setting is complete.

Now find the percentage of water required for, and the setting time of, 100 gm. of pure plaster of Paris. Then make up a solution of .25 per cent. of gelatin or glue size in the correct amount of water and use this solution instead of plain water to mix with another 100 gm. of plaster. Note the increase in setting time. Repeat with another 100 gm. of plaster mixed with a solution containing .5 per cent. of gelatin. Further tests should be made with increasing amounts of gelatin, the setting times noted and the results plotted as a graph.

**EXPERIMENT 104.**—To observe the setting of hard-burnt plaster.

As in Experiment 103 obtain the setting time of the hard-burnt plaster obtained in Experiment 102, also the percentage of water necessary for mixing. Then try the effect of small, increasing percentages of alum added to the water; as stated, with small percentages the setting time will be reduced.

A further series of experiments may profitably be carried out to show the increase in strength of hemi-hydrate plaster with small percentages of retarder.

#### 4. GYPSUM CEMENTS.

If gypsum is heated to a much higher temperature, in a kiln, than for the two types of plaster already described, it gives a very slow setting product. For this reason additions are made, to act as an accelerator, and the material re-burnt and then in some cases finely ground. Such materials are termed gypsum cements and are usually given proprietary names.

Possibly the best known of these is Keene's cement. The original material was made under patent and setting was controlled by soaking the dead-burnt gypsum in alum solution, drying, re-calcining and then grinding. It was easy working, set hard with a smooth surface after a few days, and was found to be satisfactory to receive decoration, the surface absorption being sufficient, in spite of its smoothness, to "take" paint. Many patent plasters are nowadays sold as Keene's, which are not exactly similar and which, owing to a lime content, produce failure of paint films if painted when new. Some present-day Keene's cements are thus viewed with suspicion in some quarters.

Parian cement is similar to Keene's except that borax is used in place of the alum. Sirapite is similarly treated with petroleum, and Martin's cement with potassium chloride. Selenitic cement is prepared from a feebly hydraulic lime with a small addition of gypsum plaster.

Most of these patent preparations give a hard, smooth surface which in some cases may be polished, but some of them are subject to condensation because of this, and others cause trouble by efflorescence owing to contained salts. Nevertheless they are valuable materials if their nature is understood and they are intelligently used.

## SILICA AND ALUMINA

1. *Silica and Silicates.*
2. *Alumina and Aluminates.*

## 1. SILICA AND SILICATES.

Silicon is one of the very rare elements and is a solid rather like carbon. Its importance is due to the fact that its compounds are widely distributed in nature and enter into the composition of many common materials. Silicon does not occur naturally but can be isolated in the laboratory. It burns in oxygen, yielding silicon dioxide,  $\text{SiO}_2$ , commonly called *silica*.

**Silica.**—Silica occurs in nature as quartz, a very pure form of silica, crystalline in structure, transparent and nearly as hard as diamond. Sand is another form of silica, though not so pure, and flint is also silica in an amorphous condition. Molten silica sets upon cooling to a hard glass which has a very low coefficient of expansion (see Chapter XX) and is not affected by common acids; it is therefore used for certain kinds of chemical apparatus. Silica, being a non-metallic oxide, is an acid but as it is insoluble its acidic properties are not so apparent as in the case of those which can form solutions. It thus reacts with alkalis to form salts and for this reason apparatus made of silica glass is unsuited for use with alkaline substances if they are to be heated.

**Silicates.**—The salts formed by the action of alkalis on silica are called *silicates*. For instance sodium hydroxide combines with it to form sodium silicate thus:  $2\text{NaHO} + \text{SiO}_2 = \text{Na}_2\text{SiO}_3 + \text{H}_2\text{O}$ . Silver sand (silica) melted with sodium carbonate also produces sodium silicate, thus:  $\text{SiO}_2 + \text{Na}_2\text{CO}_3 = \text{Na}_2\text{SiO}_3 + \text{CO}_2$ . Sodium silicate may also have the formula  $\text{Na}_2\text{Si}_2\text{O}_5$  depending upon the proportions in which the combination takes place. This is by no means the only silicate but is interesting as being what is known commercially as "water glass." Sodium silicate is a transparent, hard solid, rather like glass in appearance, and to produce water glass it is crushed and dissolved in boiling water. This is thus a solution of sodium silicate and is extremely viscous, but it may readily be diluted for use. Its chief uses are to preserve stonework and to harden the surface of concrete. Its action on stonework is to penetrate by absorption and dry out in the surface pores. As it is impervious to cold water it thus acts as a waterproofer, and also in the case of limestone or lime-sandstone it partially converts the calcium

carbonate into calcium silicate, also impervious. Its action on concrete is similar but in this connection it is mainly to floors that it is applied in order to give a hard surface layer which will better withstand wear and prevent "dusting."

Its domestic use is in the preserving of eggs, the shells of which are calcium carbonate through which air gains access and in the course of time permits the bacterial action which constitutes decay. By the same action as on the limestone the shell is made impervious and so the contents are sealed effectively.

CLAY.—Clay is one of the results of erosion upon igneous rocks, these being composed of silica and various silicates. The minute particles of rock are held by aluminium silicate, the mixture being extremely fine and adhesive or "sticky." When clay is heated to red heat the constituents combine and the resulting clay goods, after cooling, are hard and generally comparatively dense. If heating is more intense certain of the silicates are melted and, with proper control, the product is vitreous and therefore exceedingly dense and impervious. The characteristic colours of clay products are due mainly to various oxides present in the clay as impurities—chiefly iron oxide.

Clay is one of the two chief raw materials used in the manufacture of Portland cement, chalk or some other form of limestone being the other. These are heated up to a temperature of about 1,400 deg. Cent. when, after the decomposition of the limestone, the fusion of the clay results in combination to form pellets of cement clinker which are subsequently ground to a fine powder. The finished product is composed mainly of lime and silica, with much smaller proportions of alumina, iron oxide and various other compounds. Upon adding water to the cement the chemical action of setting commences and results, broadly, in the formation of calcium silicate and calcium aluminate. Portland cement, an essentially modern material, will be dealt with fully in the second volume.

## 2. ALUMINA AND ALUMINATES.

Like silica, alumina is one of the most widely distributed of natural substances. It is oxide of aluminium,  $\text{Al}_2\text{O}_3$ , and is found in France, the W. Indies, etc., as *bauxite*, a pure form of alumina from which metallic aluminium is obtained. It is, however, more usually found in combination in more complicated compounds and mixtures such as clay. It forms aluminates, for instance calcium aluminate, as mentioned in the previous paragraph.

## SECTION II — STRUCTURES

### CHAPTER XIII

#### CO-PLANAR FORCES

1. *Forces and their Effects upon Bodies.*
2. *Graphical Representation of Forces.*
3. *Concurrent Force Systems.*
  - (a) *Resolution of a Force.*
  - (b) *Composition of Forces.*
4. *Non-Concurrent Force Systems.*
  - (a) *Non-parallel Forces.*
  - (b) *Parallel Forces.*
5. *Couples.*

In Chapter II, page 35, we defined *force* as *that which changes, or tends to change the state of a body, whether of rest or of uniform motion in a straight line.*

This Section of the book is concerned with the investigation of the effects of forces upon materials and upon structures. This branch of science is called *mechanics*, but in Building problems we are almost wholly concerned with only one aspect of mechanics. As we have seen, bodies may be either at rest or in motion. Buildings and the component parts of buildings are required to be in a state of rest, or *in equilibrium*, under the action of all the forces which act upon them. The section of mechanics dealing with this requirement is known as *statics*. Machines are designed so as to be capable of motion under the action of forces. This section of the science is called *kinetics* or *dynamics*, and does not lie within our sphere as architects and builders.

#### 1. FORCES AND THEIR EFFECTS UPON BODIES.

The units adopted in the measurement of forces are those of weight, for we have already seen that the weight of a body is the *force* with which it is attracted to the earth. To measure forces scales could therefore be used, but this is not convenient because forces act not only vertically but in any other direction. Spring dynamometers, or as they are more usually termed *spring balances*, are used for this purpose. Let us see the effect of forces upon the spring of such an instrument.

**EXPERIMENT.—105** To note the effect of forces upon a steel spring.

Fig. 105 shows a simple experimental dynamometer. The body is of boxwood, with a longitudinal groove which accommodates the spring. This latter is fixed at the head by a screw, and at the foot is an index which moves over a scale of inches and tenths engraved on the face of the instrument. The forces are applied by means of the steel or brass weights shown in the diagram.

Fix the dynamometer securely in a clamp so that it is truly vertical and adjust the spring by means of the fixing screw so that the index coincides with zero on the scale. Now suspend the hanger from the hook on the index and note the new position on the scale. Repeat, adding one extra weight at a time, and jot down the respective readings.

Not more than half a dozen weights should be used or there is danger of spoiling the spring by overloading. The actual readings will depend upon the strength of spring used, but in Table 7 are given some actual results. The third column gives the readings as the weights are removed and these act as a check on those in column 2, also enabling a mean to be taken, so allowing for experimental error.

The results should also be plotted in graph form as in Fig. 106.

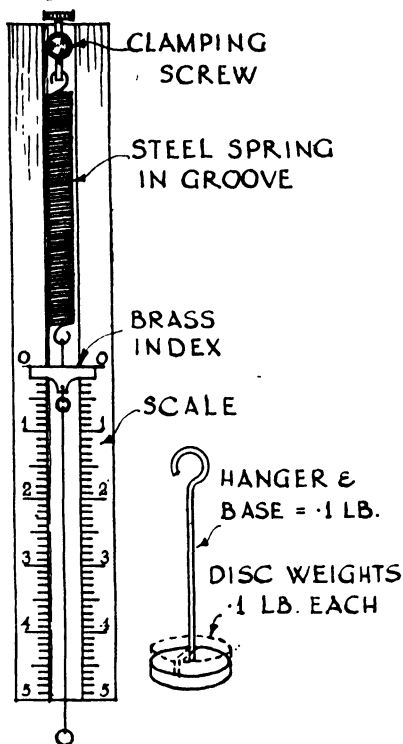


FIG. 105.—Spring Dynamometer.

TABLE 7.

Load	Reading	
	Loading	Unloading
0	0	0
.1 lb.	.71	.7
.2 lb.	1.4	1.4
.3 lb.	2.12	2.1
.4 lb.	2.85	2.85
.5 lb.	3.52	3.52

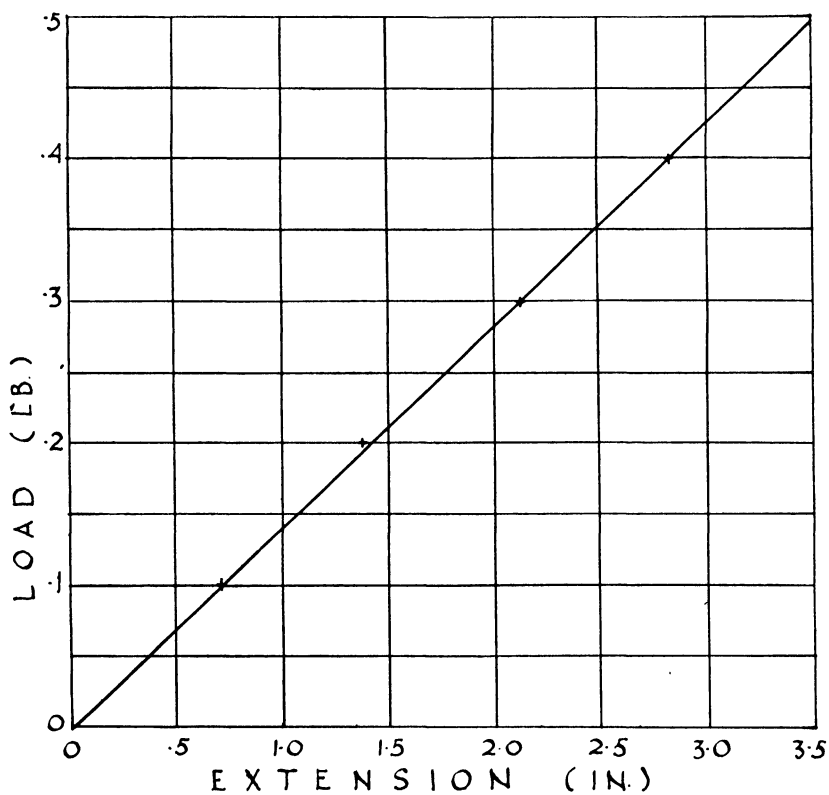


FIG. 106.—Relationship between Load and Extension of Spring.

The usual types of spring balance used in experimental work are shown in Fig. 107. Both are made of brass, with steel springs, type A being suitable for attaching to cords to measure "pulling" forces, and type B to rods for "pushing" forces. The capacity depends upon the strength of the spring and may be 5 lb., 10 lb., 20 lb., etc. The scale may be in pounds and ounces but pounds and decimals of a pound are also obtainable and are better.

Type B may be used to measure inclined forces, but for "pulling" forces that are not vertical type A balance is used in conjunction with free-running pulleys, as will be seen from succeeding experiments. The effect of a pulley of this kind is merely to alter the direction of the force; its magnitude is unaltered except for the slight friction, which cannot be eliminated. Fig. 108 shows how a vertical force applied by means of weights can be converted by a single pulley into a horizontal or inclined force. This is very convenient in force experiments because if all forces had to be arranged in a vertical plane matters would be complicated by the weight of the balances and cords.

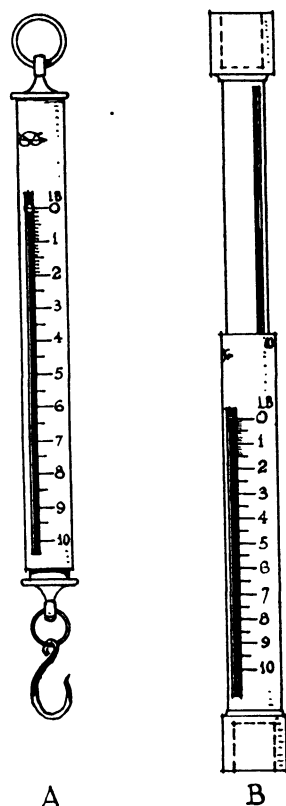


FIG. 107.—Spring Balances.

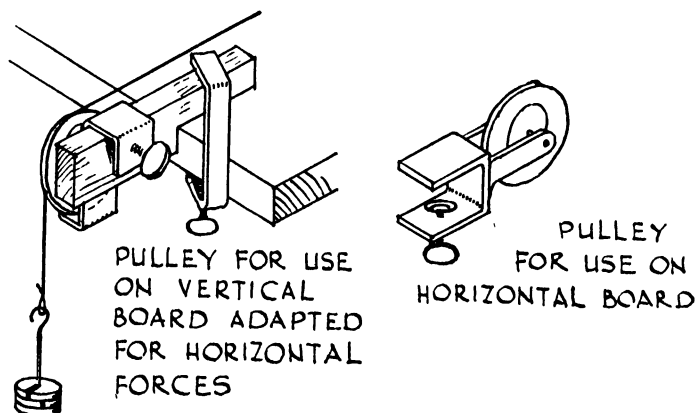


FIG. 108.—Use of Fixed Pulleys for changing Direction of a Force.



**TRANSMISSIBILITY OF FORCE.**—*A force may be assumed to act at any point in its line of action.* This is called the *principle of the transmissibility of force*. The *line of action* is the direction of the force, indicated in the experiment by the cords.

**EXPERIMENT 106.**—To show that force may be transmitted through a body.

Cut a piece of thin plywood to an irregular outline as shown in Fig 109 and support it on a horizontal board by means of three small steel balls so that it may move easily in any direction in a horizontal plane. Fix two panel pins near the edge, opposite to each other, and to these attach cords running over pulleys and having weights hung from their ends. In whatever position the plywood is placed it will, under the action of the two forces pulling upon it, always assume such a position that an imaginary line joining the two pins A and B lies in the same straight line as the two cords. In other words the line of action which is common to both forces continues through the body. This is true whatever the magnitude of the forces.

The same principle applies when a body is in equilibrium under the action of more than two forces. In such a case the lines of action cannot be in the same straight line, but they always intersect at a point.

**EXPERIMENT 107.**—Repeat the last experiment but with three forces instead of two.

At least three pins and pulleys will be required as shown in Fig. 110, and if the directions of the cords be continued by pencil lines drawn on the plywood disc they will be found always to meet at a point O. The position of this point will, of course, vary according to the forces employed, but for every system of loading there will be a single point O at which the various lines of action meet.

We have earlier mentioned “pulling” forces and “pushing” forces. A pulling force is called a *tensile force* or *tension*, and its effect upon a body is to tend to cause it to stretch or lengthen. A pushing force is called a *compressive force* or *compression*, and it tends always to produce crushing or shortening of a body. The effects of these principal types of force can best be demonstrated by experiments on rubber, this material being one which is very susceptible to the effects of quite small forces.

**EXPERIMENT 108.**—To show the effect of tension upon rubber.

Remove the spring from the experimental dynamometer used in Experiment 105 and substitute a suitable length of  $\frac{1}{4}$ -in. square rubber cord. Now repeat Experiment 105, set down the loads and extensions both during loading and unloading, and plot a graph showing the behaviour of the rubber under load. Extension will be found to be proportional to the load, and the graph will be a straight line as in Fig. 112.

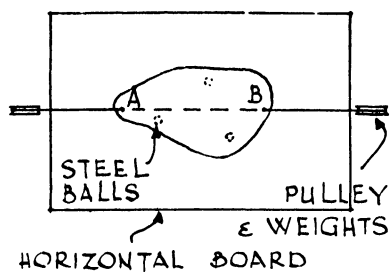


FIG. 109.—Transmission of Force through Rigid Body.

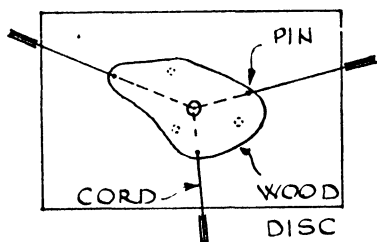


FIG. 110.—Rigid Body acted upon by Three Forces.

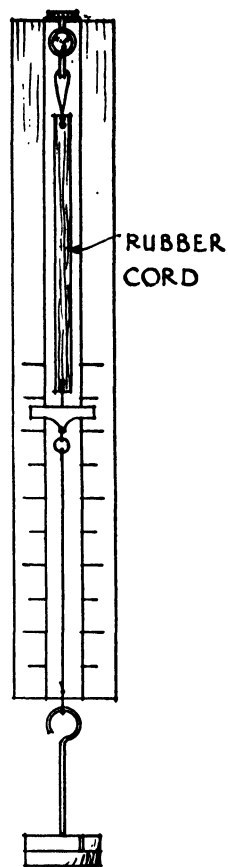


FIG. 111.—Effect of Tension upon Rubber.

TABLE 8.

<i>Load</i>	<i>Length</i>	<i>Extension (Loading)</i>	<i>Extension (Unloading)</i>
0 lb.	3.6-in.	0-in.	0-in.
.5 lb.	3.81-in.	.21-in.	.21-in.
1.0 lb.	4.03-in.	.43-in.	.43-in.
1.5 lb.	4.67-in.	.64-in.	.635-in.
2.0 lb.	5.53-in.	.86-in.	.86-in.

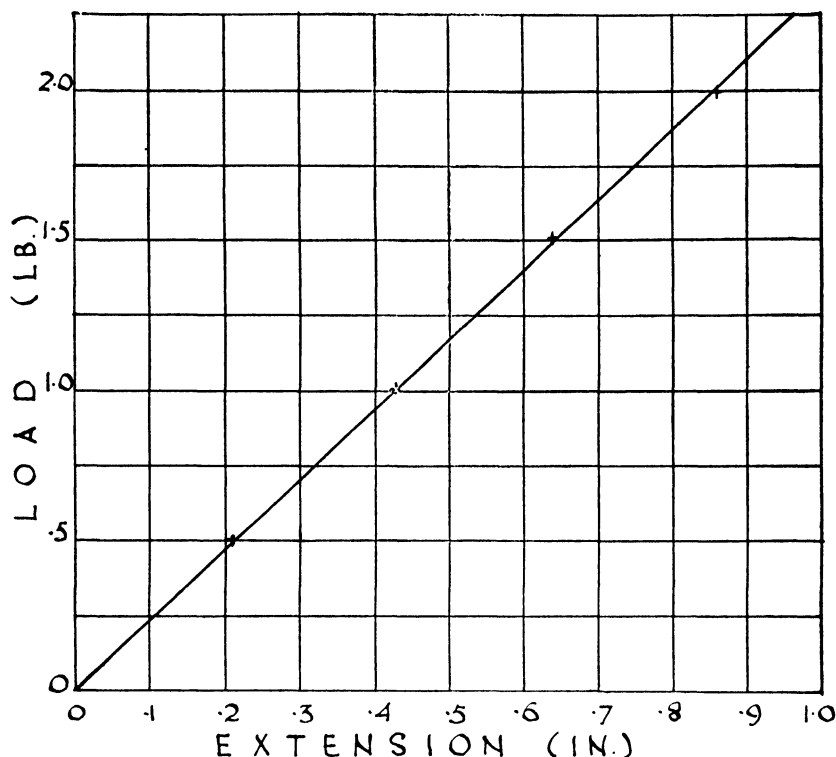


FIG. 112.—Relationship between Load and Extension of Rubber.

EXPERIMENT 109.—To show the effect of compression upon rubber.

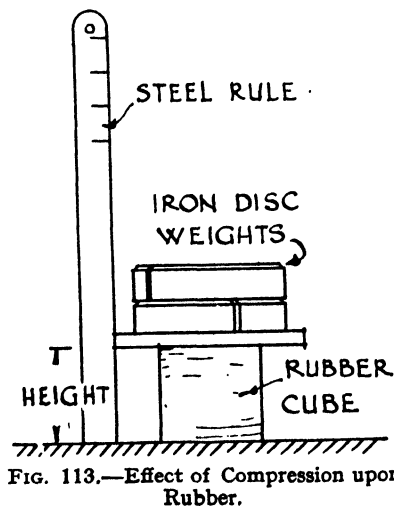


FIG. 113.—Effect of Compression upon Rubber.

A block of rubber 2-in. or 3-in. cube is placed on a level surface and large iron disc weights, say 1-lb. or 2-lb. each, placed carefully on top as shown in Fig. 113. The height of the block is measured with a steel rule each time a weight is added and again as it is removed, and the results set out as in Table 9 and the graph, Fig. 114. Each height is measured on all four sides of the block and the mean taken. This is necessary because of the difficulty of applying the loads perfectly central. If a small testing machine is available it should be used in preference to the method described.

TABLE 9.

<i>Load</i>	<i>Height</i>	<i>Shortening (Loading)</i>	<i>Shortening (Unloading)</i>
0 lb.	4.0-in.	0-in.	0-lb.
2 lb.	3.625-in.	.375-in.	.375-lb.
4 lb.	3.25-in.	.75-in.	.75-lb.
6 lb.	2.875-in.	1.125-in.	1.125-lb.
8 lb.	2.5-in.	1.5-in.	1.5-lb.

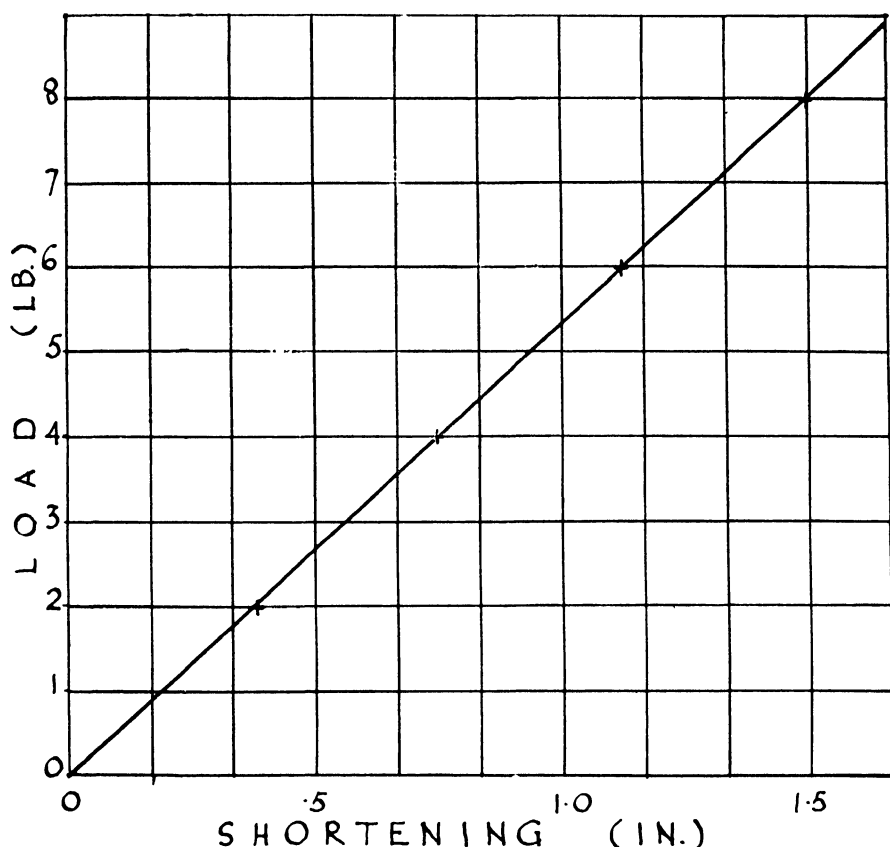


FIG. 114.—Relationship between Load and Shortening of Rubber.

In both experiments the effect of loading the rubber was to alter its length or height, in other words the rubber was deformed or changed in shape, temporarily at least. This deformation is called a *strain*. But, within the limits of the loading, the rubber did not break; it therefore resisted the action of the load. Now force can only be resisted by force,

so that the resistance of the rubber took the form of providing another force to balance the load, an internal force (within the rubber itself) to oppose the applied force (the load). This internal force is called *stress*.\*

Stress and its effects are discussed at length in the next chapter, but this brief explanation is a necessary preliminary to our study of the equilibrium of forces.

**REPRESENTATION OF FORCES.**—Referring to Fig. 110, we have three forces all of which are acting at the point O. To illustrate the experiment we show the solid body, pins, cords, pulleys, etc., but if we wish to represent this system of forces in a general way we do so as shown in Fig. 115. Here the point O is indicated and the three forces are shown merely by straight lines, each giving the *direction* of the force, and arrowheads, each denoting the *sense* of the force. These two terms may be a little confusing at first because the technical meaning of the term “direction” is rather different from its everyday meaning. The direction of a force is its line of action, but the force may act along this line in either of two opposite ways. The point O is the *point of application* of the force, and the force may act towards O or away from O; this is what is meant by “sense,” and the arrowhead in each case makes the sense of the force clear.

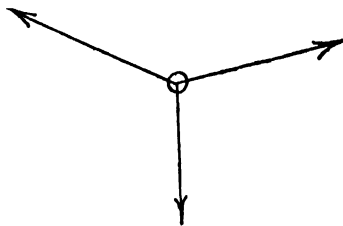


Fig. 115.—Representation of Forces acting in a Plane.

In Fig. 115 the arrows are “pulling” away the the point O and this indicates that the forces are tensile forces. If the arrows were “pushing” towards point O they would represent compressive forces. This is an easy way of remembering the sense of forces:—“pulling” for tension, “pushing” for compression.

In Fig. 116, A, a block of material is shown supporting a 4-lb. weight. This force of 4-lb. is transmitted through the block to the ground. For equilibrium the ground must therefore exert an equal force upwards to balance it as shown at B. The downward load is an applied or active force or *action*, and the upward balancing force is a passive force or *reaction*. A reaction is non-existent until produced by an applied force; the two must always be equal and opposite. (For clearness we are ignoring the weight of the block itself which would of course act along with the applied force, the reaction being equal to the sum of these.) On the top and base of the block therefore a force of 4-lb. is acting, and in resisting crushing the material must provide an equal resisting force to balance these, as shown at C. This resisting force or stress is of 4-lb. and it acts

\* Strictly it is the dual action of the applied force and the resisting force which constitutes *stress*, but the above explanation is simpler to understand.

upwards and downwards with equal intensity. Note that there is not a total of 8-lb. of stress, nor is the stress of 4-lb. split into 2-lb. acting upwards and 2-lb. acting downwards; if we apply a force of  $x$ -lb. to a body the stress in the body is also  $x$ -lb., the reaction is not another applied force but merely a force automatically produced in order to preserve equilibrium and cannot be considered to contribute to the amount of the stress. It should rather be thought of as an alternative cause of the stress. At D is shown the method of representing the stress, in this case compression, which agrees with the preceding paragraph.

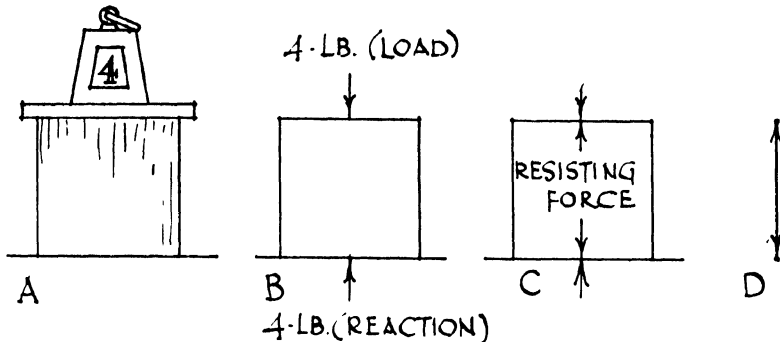


FIG. 116.—Action and Reaction.

## 2. GRAPHICAL REPRESENTATION OF FORCES.

In this volume we are dealing only with systems of forces which are *co-planar*, or all of which are acting in a single plane. The bars of a roof truss all lie, theoretically, in the same plane; the loads coming on to the truss from purlins, etc., are also in this same plane since they act at the points of contact with the truss. These forces may all be represented simply and correctly on a plane such as a blackboard or sheet of paper. The bars of a derrick tower, on the other hand, do not lie in one plane; these forces are not co-planar and therefore cannot be represented simply on a plane surface.

The graphical treatment of problems in Statics is termed *graphic statics* and provides a useful alternative to mathematical solutions. In some respects it is to be preferred since any error in the process is soon evident, and with careful draughtsmanship results may be obtained correct to less than 1 per cent. In view of the approximation of most of the data assumed in such problems this degree of accuracy is as a rule more than sufficient.

**SCALARS.**—All mathematical quantities may be represented by straight lines drawn to scale and the ordinary mathematical operations such as addition and subtraction carried out graphically. For instance,

suppose a man has four shillings and subsequently acquires a further three shillings we should solve the problem of his assets mathematically thus:  $-4s. + 3s. = 7s.$  Graphically, representing each shilling by a straight line say 1-in. long we could draw one line 4-in. long to represent 4s., continue in the same line (see arrow heads in Fig. 117) for a further 3-in. to represent 3s., and then measure the total length of line (7-in.) to give us the total sum, 7s. Similarly we can subtract quantities, say three shillings from four shillings graphically as in Fig. 117. Any quantity which can be completely represented mathematically by a number may be represented graphically in this way, for instance amounts of money, distance, temperature, time, etc., etc., and such a straight line is called a *scalar*. But, as will already have been concluded, this graphical solution is slow and clumsy as compared to mathematical solution. Nevertheless it is utilized to advantage in the slide rule where operations of multiplication and division of numbers are done by adding or subtracting distances representing to scale the logarithms of the numbers.

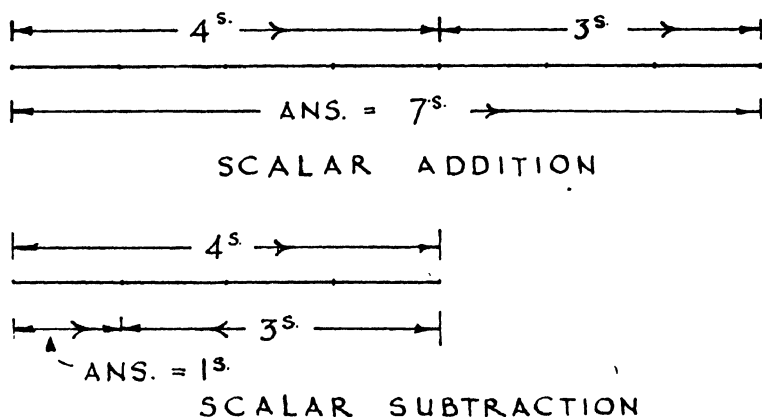


FIG. 117.—Graphical Addition and Subtraction by Scalars.

**VECTORS.**—Forces, on the other hand, can be dealt with more easily graphically than mathematically, for a force cannot be completely represented by a number. A force has not only magnitude but also direction, sense and usually a point of application. Therefore unless a number of forces are acting in the same straight line (which is unusual) they cannot be dealt with exactly as in Fig. 117. The graphical representation of a force is known as a *vector*; this is really a special form of scalar and is a straight line drawn from or to a particular point, of definite length, at a definite angle, and with an arrow head. Fig. 118, for instance, is a vector representing a compressive force of 3-lb. acting at point O at an angle of 45 deg.

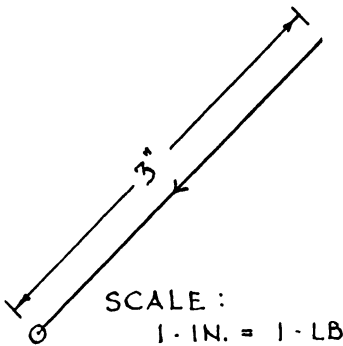


FIG. 118.—Use of Vector to represent a Force.

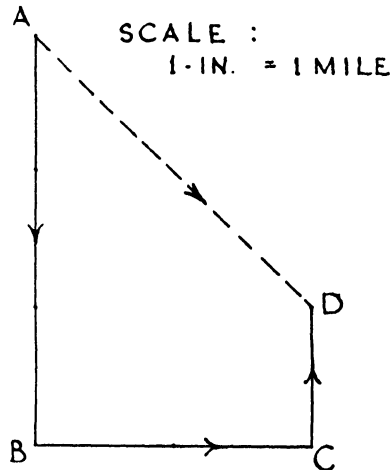


FIG. 119.—Vector Addition.

**VECTOR ADDITION.**—Besides forces, vector quantities include velocities and displacements, etc. Suppose a man, starting from a definite point A, walks due south for a distance of three miles, then changes direction to due east for two miles, then due north for another one mile to reach his finishing point. We can represent his walk as in Fig. 119 where AB, BC and CD are vectors representing the three instalments of his walk. From this it will be seen that if, instead, he had merely walked south-east for approximately 2·84 miles he would have reached his destination. AD is the vector representing this alternative walk which is the “sum” or *resultant* of the other three walks. To get back to his starting point he may either retrace his steps along DC, CB and BA, or alternatively he may merely walk from D to A. DA, its arrow head pointing towards A, is the *equilibrant* of AB, BC and CD, and is thus equal to and opposite to the resultant.

We shall see later that forces too may be dealt with in this way with much greater facility than by the rules of mathematics, which in these cases involves the employment of trigonometrical methods.

### 3. CONCURRENT FORCE SYSTEMS.

Forces are termed *concurrent* when they act at a single point, or when their lines of action meet at a point.

**Resolution of a Force.**—A resultant may be the equivalent of one, two, three, in fact any number, of vector quantities. Advantage is taken of this fact, in connection with forces, where we may wish to



substitute a single force for a number of forces, or to substitute a number of forces for a single force. We shall deal first with the latter of these two cases ; in practice it is usual to require the force to be resolved only into two other forces.

Suppose we have, as in Fig. 120, a force AC acting upon a body but not in a direction perpendicular to its surface. The effect of the force upon the body can most readily be investigated when the force is acting at right-angles or perpendicular to it. We can therefore substitute for this inclined force a vertical one and a horizontal one, the latter obviously having no effect so far as compression of the body is concerned.

To determine the magnitude of the vertical force DC we may make use of a principle which we may state :—" The vector of a single force may be completely represented by those of any two forces, acting at the same point, which form adjacent sides of a parallelogram of which the vector is the diagonal." The construction in Fig. 120 will make the method clear. Set off five units of length from C along CA—this is the vector of force AC. Then from C draw a vertical line CD and a horizontal line CB and complete the parallelogram (in the present case it is a rectangle). AC is now the resultant of DC, BC, and the magnitudes of these, to the same units as AC, is found to be four tons and three tons respectively. Force DC is the one inducing compression of the body and force BC produces none.

In this case we have *resolved* the force AC into two *component forces*, DC and BC and, as will be seen from Fig. 121, there is no limit to the number of possible pairs of component forces ; in all cases other than in Fig. 120, however, they do not help us in the problem because we have more than one force producing the effect upon the body.

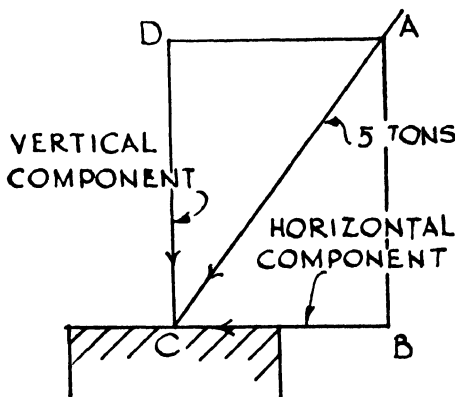


FIG. 120.—Resolution of a Force into Two Components.

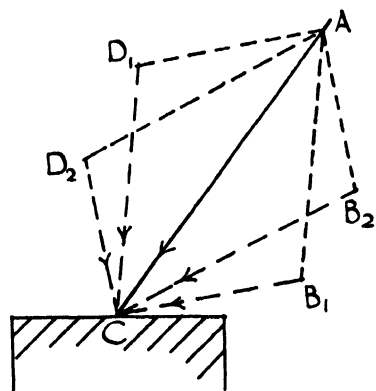


FIG. 121.—Other possible Pairs of Components.

The converse of this principle is called the *parallelogram of forces*. This is:—*If two forces acting at a point be represented in magnitude and direction by adjacent sides of a parallelogram drawn from that point, their resultant is represented by the diagonal drawn from the point.* Fig. 122 shows an application of this principle and represents two forces acting at a point on the rafter of a roof truss. The vertical force is the load from a purlin and the inclined force (perpendicular to the rafter) is the active component of the horizontal wind pressure. To determine the stresses acting in the bars of the truss it is desirable to replace the two by a single force, and this is done by setting out the magnitudes of the two forces, completing a parallelogram and drawing in the diagonal. This, to the same scale, is their resultant.

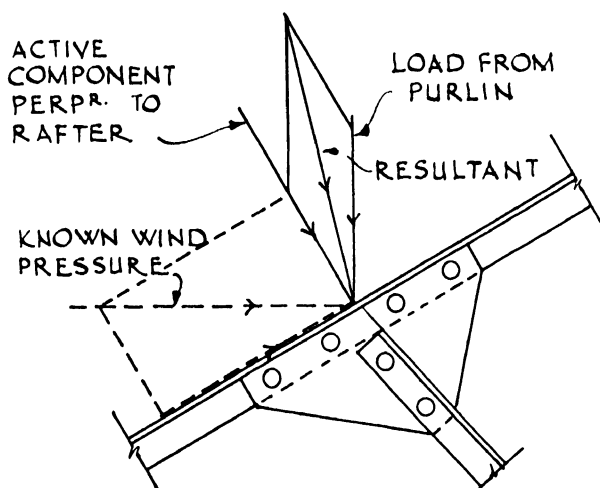


FIG. 122.—Example of Resolution of a Force (Horizontal Wind Pressure) and Composition of Two Forces (Active Component and Load).

**EXPERIMENT 110.**—To demonstrate the parallelogram of forces.

This principle may be verified experimentally as shown in Fig. 123. A drawing board is arranged to stand vertically, and two pulleys clamped to the top edge. A string loaded at the ends with  $\cdot 3$  lb. and  $\cdot 4$  lb. respectively is laid over the pulleys and another string attached to it carrying  $\cdot 5$  lb. The strings A and B will take up the positions shown (at right-angles to each other). Pin a sheet of paper on the board and mark on it their positions, mark off 3 units along string A and 4 units along string B, complete the parallelogram shown and draw the diagonal. This will be found to be vertical (in line with the third string) and 5 units along.

**Composition of Forces.**—If we wish to substitute a single force for a number of forces, in other words to find their resultant or equilibrant, the process is called *composition* and is the converse of resolution. If

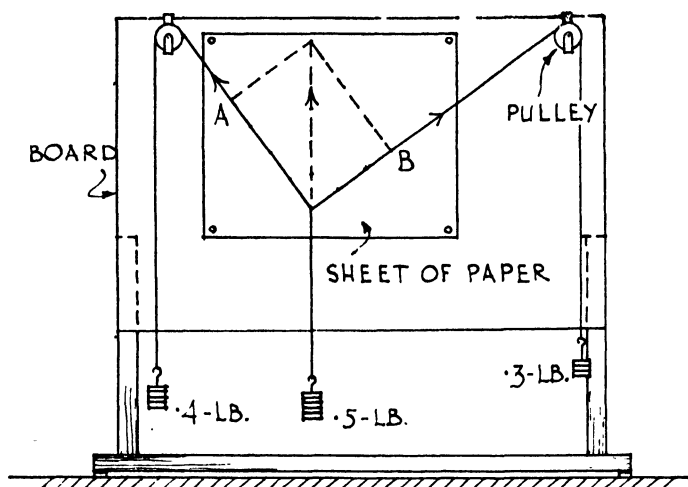


FIG. 123.—The Parallelogram of Forces.

only two known forces are involved, the principle of the parallelogram of forces may be utilized as in resolution, but there are generally more than two.

**EQUILIBRIUM OF THREE CONCURRENT FORCES.**—Let A, B and C (Fig. 124) be three forces meeting at point O and in equilibrium. To a scale of, say, 1-in. to 1 lb. draw the vector representing force A. From

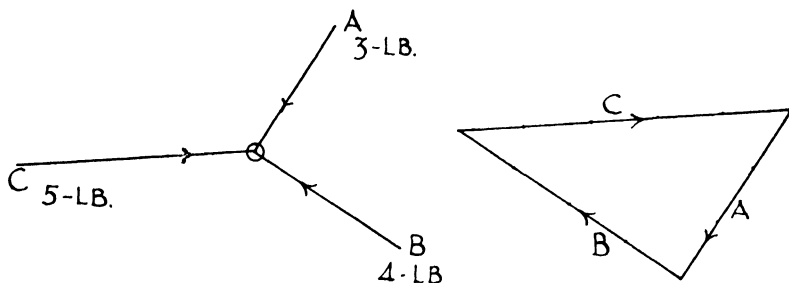


FIG. 124.—Equilibrium of Three Concurrent Forces.

the end of this draw vector B and similarly vector C. The three vectors together form a closed figure, in this case a triangle, if the forces are in equilibrium. This case is of such common occurrence that it is called

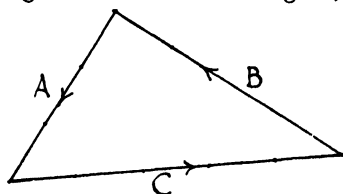


FIG. 125.—The Triangle of Forces.

the principle of the *triangle of forces* and may be stated thus:—*If three concurrent forces are in equilibrium they are represented completely by the sides of a triangle taken in order and*

*drawn parallel to their directions.* The order in which the vectors are drawn is immaterial, as will be seen from Fig. 125 where they are taken in the order A, C, B. (Compare with Fig. 124.)

It will be apparent that, when only three forces are involved, this construction may be considered as an alternative to the parallelogram of forces, for in Fig. 124 C is the equilibrant of A and B, B is the equilibrant of A and C, and A of B and C.

**EXPERIMENT 111.**—To verify the triangle of forces.

Arrange a drawing board to stand horizontally clear of the table and fix pulleys, weights and spring balance as shown in Fig. 126. Adjust the positions of the pulleys until the balance gives a reading of  $\cdot 5$  lb. and then measure the angles between the strings. These will be found to correspond with those in Fig. 124. Now arrange the two weights so that the forces they represent are acting in the same straight line (Fig. 127). The balance reading will be the sum of the two forces,  $\cdot 7$  lb.

Next move them so that the angle between them is, say,  $20^\circ$ . and again note the balance reading. Next alter the angle to, say,  $40^\circ$ . noting the reading, and so on until the angle is  $180^\circ$ .

The reading on the balance, which is the equilibrant of the two forces, is maximum when the angle is  $0^\circ$ . and decreases until at  $180^\circ$ . it is zero.

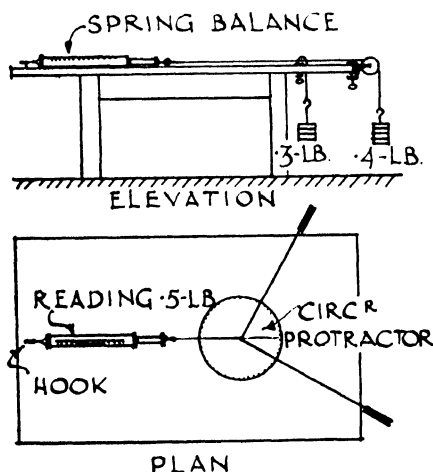


FIG. 126.—Experimental Verification of Triangle of Forces.

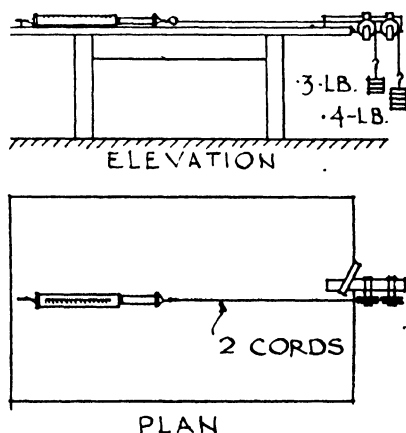


FIG. 127.—Experiment on Equilibrant of Two Forces.

In this experiment it has been observed that, except when the two forces are in line with each other, the magnitude of their equilibrant is less than the sum of the two. From this it will have been concluded that a single force may act so as to give rise to other forces much greater than itself. This is so, and is the reason why the bars of a framework such as

a roof truss are arranged to make large angles with each other—the more acute the angle the greater the force to be carried by the bar. Experiment 112 shows this in a simple manner.

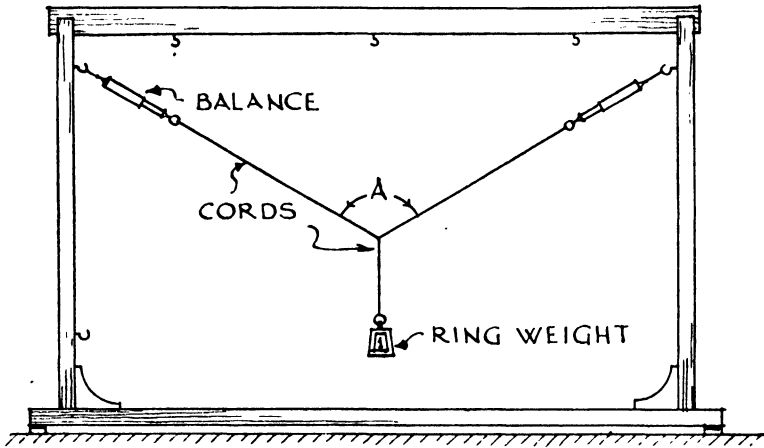


FIG. 128.—Frame for Experiments on Forces.

#### EXPERIMENT 112.

Fig. 128 shows a simple wooden frame used for experimental work on forces. Brass cup hooks may be screwed to the sides or head in any required position. For the present experiment attach spring balances to hooks near the top corners and join them by a string to which is attached a second string supporting an iron weight of, say, 1 lb. Holding a protractor behind the strings measure angle A and note the balance readings. Now, by altering the length of the upper string, vary the angle and, keeping the same weight of 1 lb., note the new readings. Check these by drawing a triangle of forces for each case and scaling off the amounts of the tensions in the upper string. (Fig. 129.)

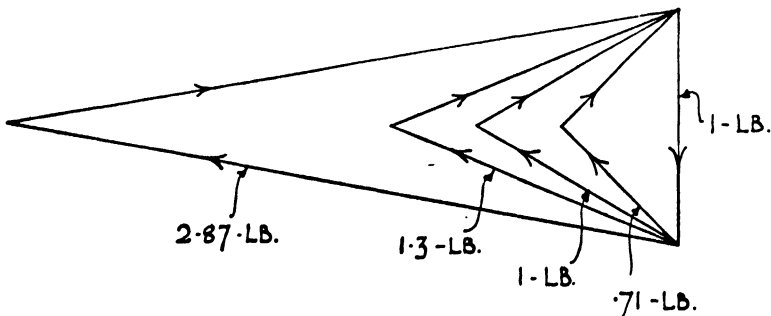


FIG. 129.—Variation of Component Forces with Angle between them.

TABLE 10.

<i>Angle between strings</i>	<i>Balance reading</i>	<i>Graphical result</i>
90 deg.	·72 lb.	·71 lb.
120 „	1·05 „	1·0 „
135 „	1·30 „	1·30 „
160 „	2·90 „	2·87 „

Note that in this experiment it is impossible for the angle to be 180 deg. for then a triangle of forces could not be drawn as the sides would never meet and the tensions would be infinitely great. When we approach this point we need a rigid body (a beam) instead of a string, and the solution of the problem involves an entirely different principle, which will be considered later. Note also that so long as we know one force fully we need only know the directions of the other two and we can find their sense and magnitude.

THE POLYGON OF FORCES.—If a concurrent force system consists of more than three forces their vectors form a closed polygon if they are in equilibrium; if not, then the force required to produce equilibrium (their equilibrant) is represented by the vector necessary to close the figure.

Consider the four forces in Fig. 130. To find whether they are in equilibrium draw the vector or “reciprocal” diagram (the “Polygon of Forces”), dealing with each force in turn and for uniformity taking them in clockwise order. It is found that to close the polygon we have to draw a further line (shown dotted in the vector diagram). This is the vector of the equilibrant or resultant, according to the sense. Transferring the direction and sense of this vector to the space diagram this indicates the equilibrant, or the resultant, of the four forces.

To be sure of the sense of this *closing line* in the vector diagram and thus to know whether it represents the equilibrant or the resultant, we should draw the vectors in turn and the arrowheads on the vectors will then follow each other around the diagram, including that of the *equilibrant*.

Consider the group of concurrent forces shown in Fig. 131. Here two of the forces are known only in direction, and it is required to find their sense and magnitude. Commence by drawing vectors for the known forces, in clockwise order. Then the vector shown dotted in the vector diagram would be their resultant, and all that is then required is to complete a triangle of forces by adding the vectors for the unknown forces. The magnitude of these may then be scaled off and their sense taken from the arrowheads which, as before, follow each other. The

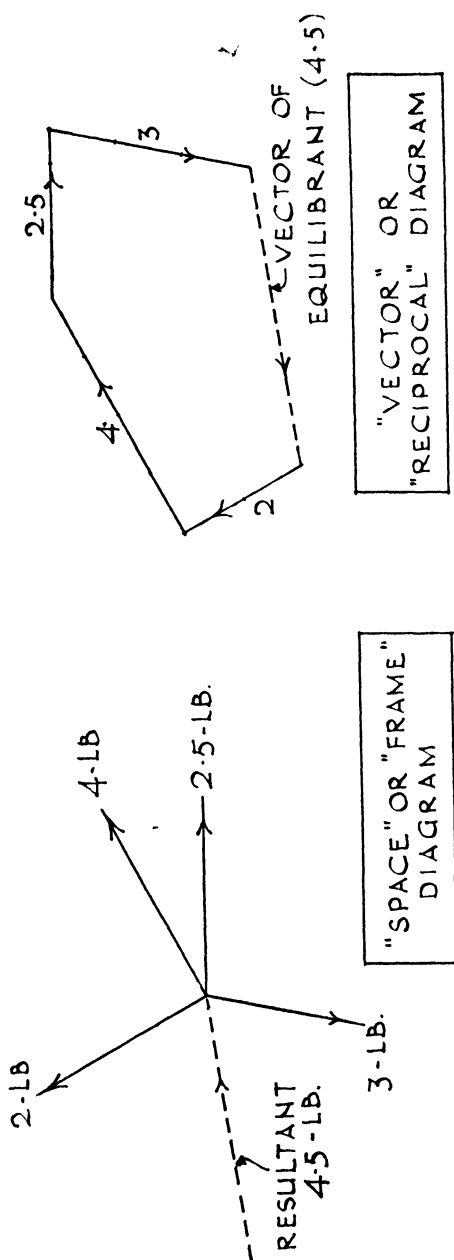


FIG. 130.—The Polygon of Forces.

dotted vector need not be drawn, or even considered, but is shown and explained in order to make the procedure clear.

These cases are easily checked with weights and pulleys experimentally.

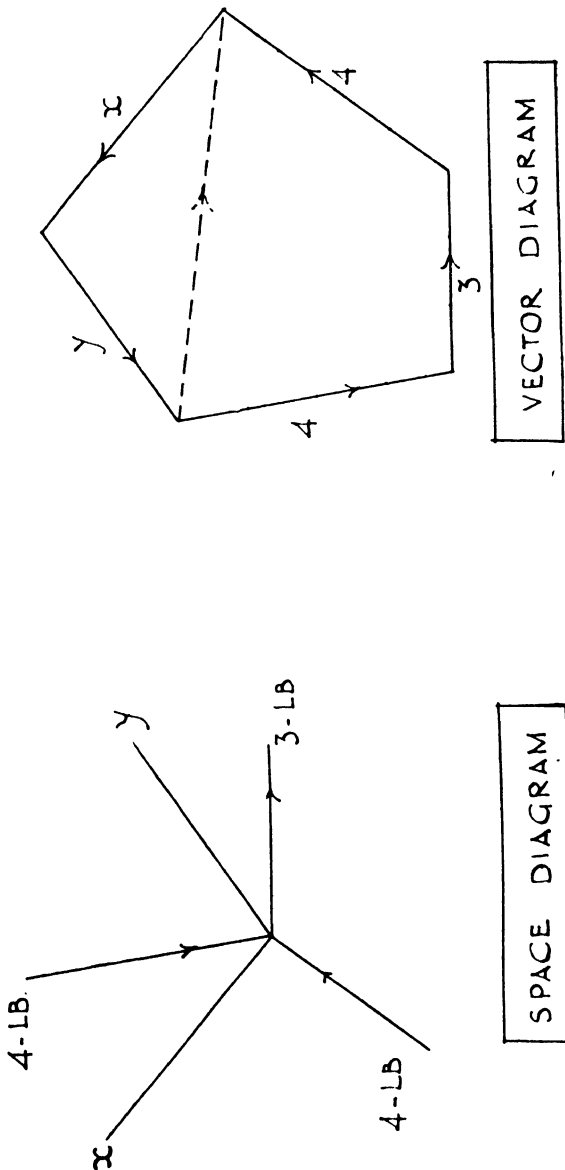


FIG. 131.—Solution of Unknown Forces in a System.



## EXPERIMENT 113.

Arrange the board, weights and pulleys as in Fig. 132 to give a system of four forces in equilibrium (the positions and amounts may be varied). Transfer the point of application and the directions of the forces to a sheet of paper, either direct as shown (to be preferred) or by measuring the angles. Draw the space diagram (Fig. 133) and name with capital letters the spaces between the forces. This method of naming the forces is called *Bow's Notation* and its advantage over merely indicating each force by a single letter, or not naming it at all, will be apparent from the vector diagram. Each force is called by the letters on either side of it; thus our forces are AB, BC, CD and DA. Suppose we first draw the vector for force AB, we name this vector by placing *a* at its commencement and *b* at its termination, according to its sense. Proceeding clockwise the next force to be dealt with is BC; as its vector will be vector *bc* it must obviously start from point *b*, and we shall not commit the error of starting it from point *a*, as is possible with other methods of notation. Complete the vector diagram and scale off the magnitudes of the forces, comparing with the experimental results.

It will be seen that, by using Bow's Notation not only are the arrowheads "cyclic" but the small letters naming the vectors also proceed around the diagram in order. Bow's Notation will be used in all future examples.

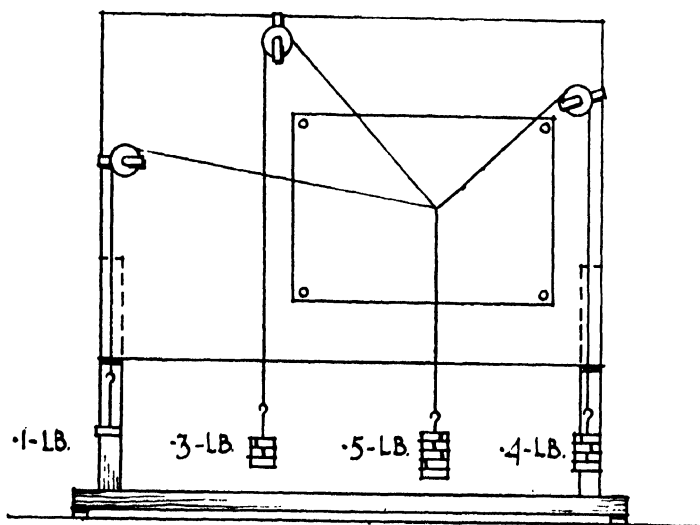


FIG. 132.—Polygon of Forces Experimentally.

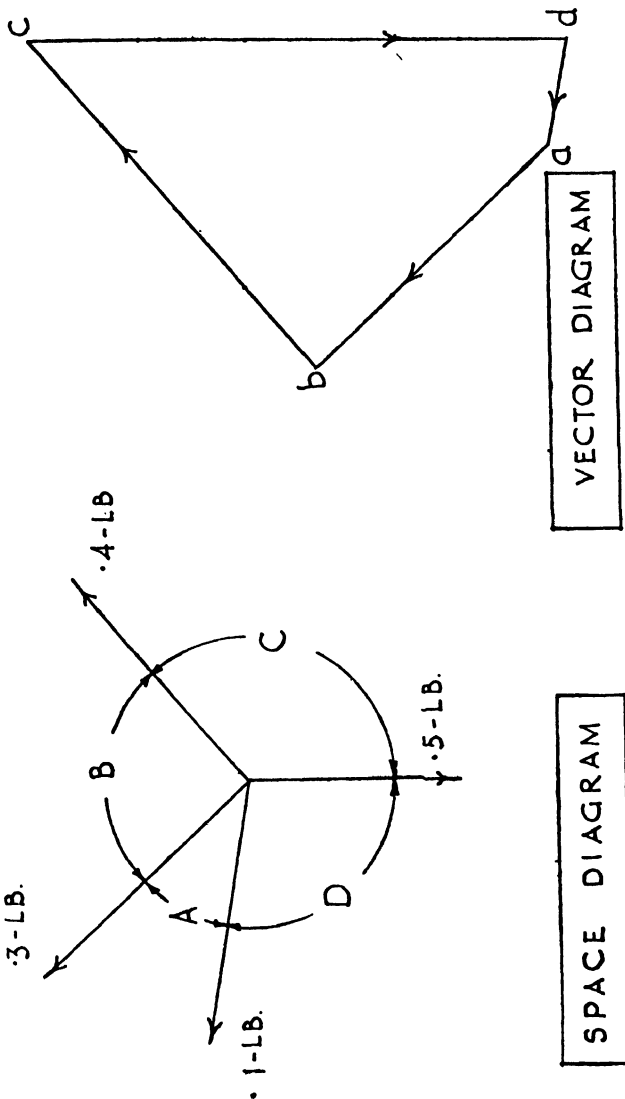


Fig. 133.—Illustrating Bow's Notation.

#### 4. NON-CONCURRENT FORCE SYSTEMS.

Non-concurrent forces are those all of which do not meet at a common point. They may be parallel to each other (for instance a system of vertical forces) or non-parallel.

**Equilibrium of Non-Parallel, Non-Concurrent Forces.**—In Fig. 134 are shown three forces which are non-concurrent. It is required to determine whether they are in equilibrium, and if not, to find their equilibrant.

Using Bow's Notation name the forces AB, BC, CD, and draw the vector diagram, from which the equilibrant is seen to be represented by vector  $da$ . This, as in concurrent force systems, gives us the magnitude, direction and sense of the equilibrant, but as the forces do not act at a common point we have still to find its position in the space diagram.

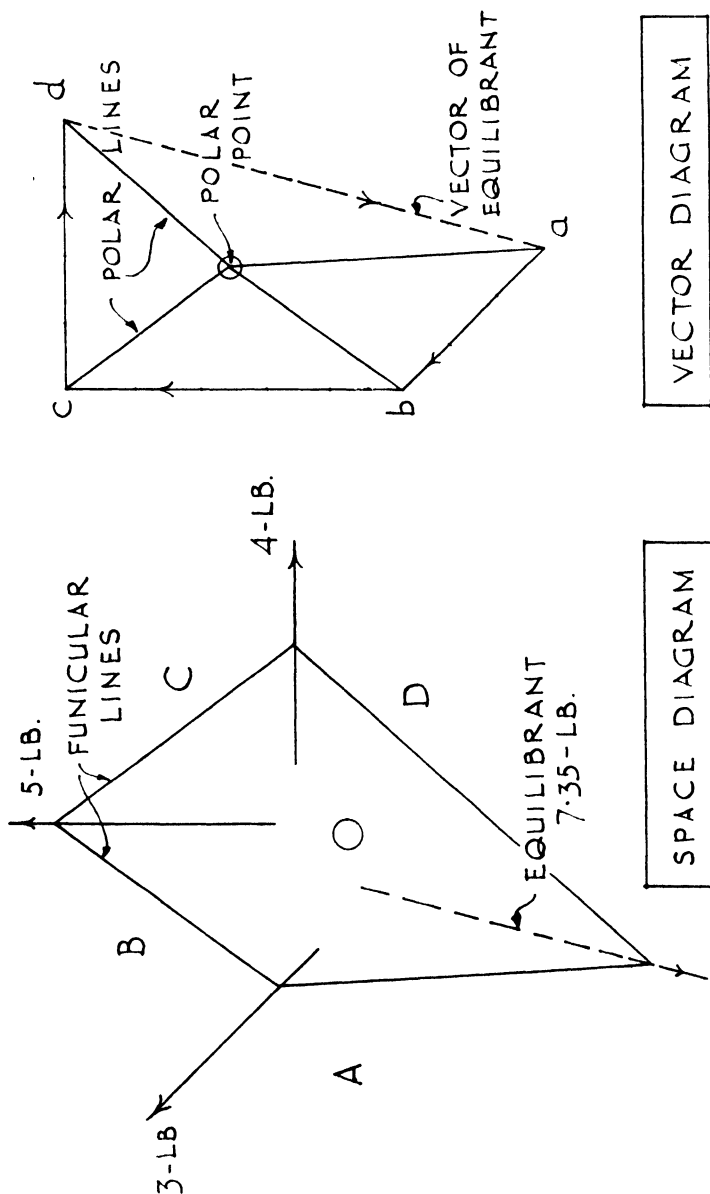


FIG. 134.—Equilibrium of Non-Concurrent Forces—Example 1.

To do this, select any point  $O$ ; this is called the *pole* or *polar point*. Join  $O$  to  $a$ ,  $b$ ,  $c$  and  $d$ , giving *polar lines*  $aO$ ,  $bO$ ,  $cO$  and  $dO$ . Now, in the space diagram, complete the naming of the spaces by inserting  $O$  in the space beneath the others. Draw, in the space diagram, the line  $AO$ , named like the other forces by the letters on either side, parallel to polar line  $aO$ . Then draw line  $BO$  parallel to polar line  $bO$ ,  $CO$  parallel to  $cO$ , and  $DO$  parallel to  $dO$ . Then the point of intersection of  $AO$  and  $DO$  is a point in the line of action of the equilibrant, which we can now draw in, parallel to its vector  $da$ .

Lines  $AO$ ,  $BO$ ,  $CO$  and  $DO$  are called *link* or *funicular lines* and together form a *link* or *funicular diagram*. Fig. 135 shows an instance in which the polar point is placed outside the vector diagram. This has the effect of giving a rather different appearance to the funicular diagram, but the procedure is identical to that in the previous case. Experience alone will show the best position for the polar point as this will govern the outline of the funicular diagram and all such diagrams should be well-conditioned. As a rule, if the vector diagram is long and narrow the pole is best outside the diagram, and *vice versa*. It will be seen later that, when the forces are parallel, the vector diagram is a straight line; we then have no option in placing the polar point.

The method of checking these cases experimentally will be clear from Fig. 132.

**Equilibrium of Parallel Forces.**—From the foregoing examples of non-parallel forces the method of finding the equilibrant, or the resultant, of parallel forces need require little explanation. Referring to Fig. 136 we have four forces acting vertically downwards. The vector diagram therefore takes the form of a straight line, and the equilibrant will be a vertical force equal to the sum of the four forces and acting through a point found by producing the first and last funicular lines to meet.

The example shown in Fig. 137 is given as it differs in points of detail because the forces are not all acting with the same sense. In such a case the vector diagram may present difficulty until it is realised that the vectors overlap each other to a certain extent. To clarify this point they are shown separately alongside the vector diagram. A straight-line vector diagram such as this is sometimes referred to as the *line of loads*.

**MOMENT OF A FORCE.**—When a number of forces acting on a body do not act at the same point their effects upon the body depend upon their positions as well as upon their magnitudes and directions. In investigating this problem we must first consider the effect of a single force about a point outside its line of action.

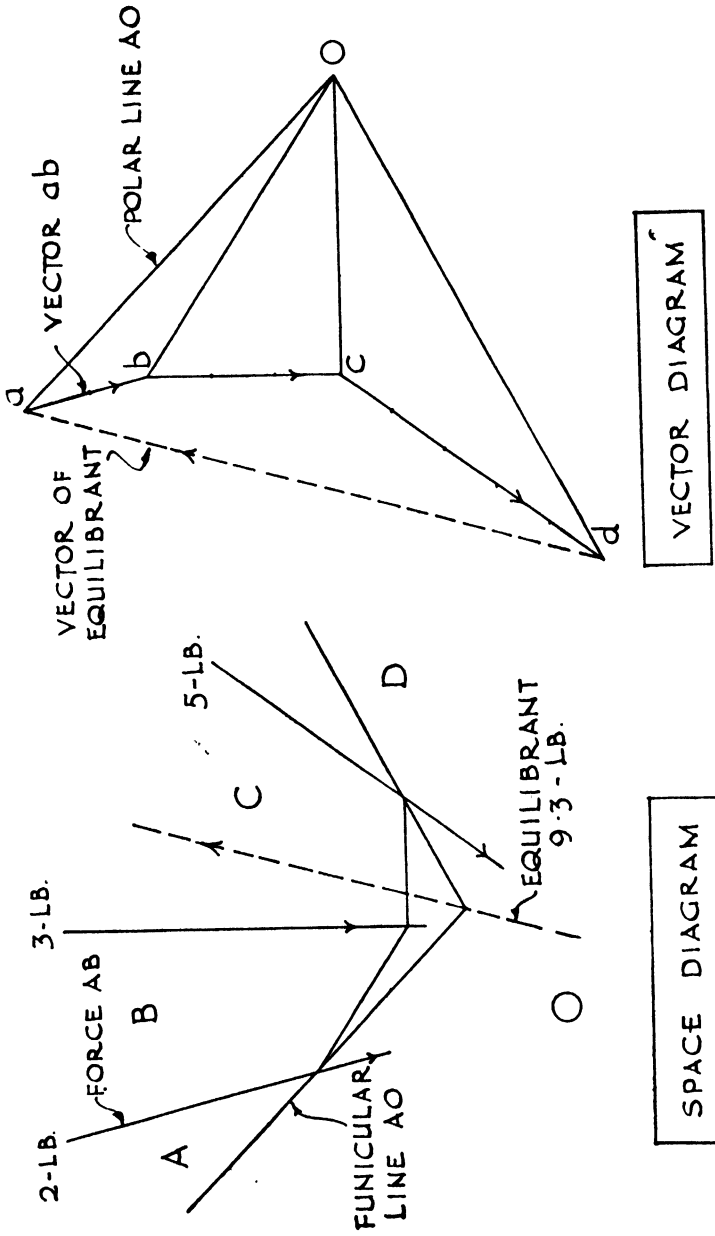


FIG. 135.—Equilibrium of Non-Concurrent Forces—Example 2.

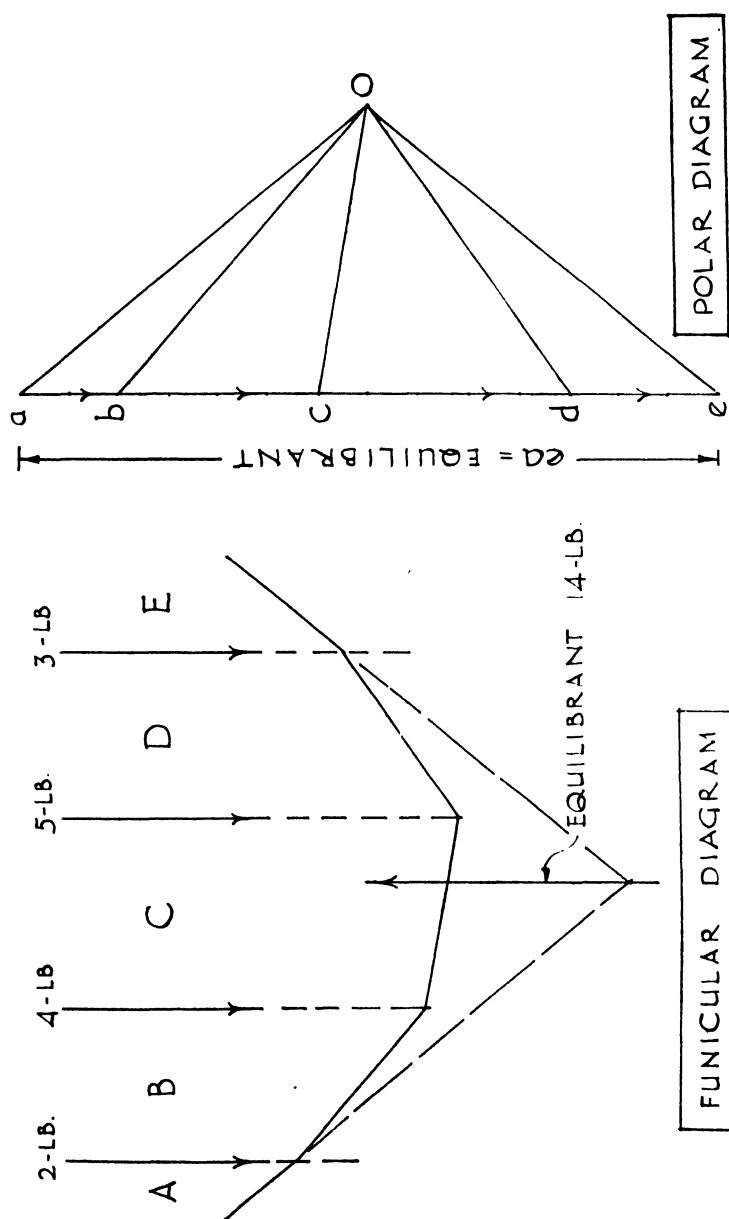


FIG. 136.—Equilibrium of Parallel Forces—Example 1.

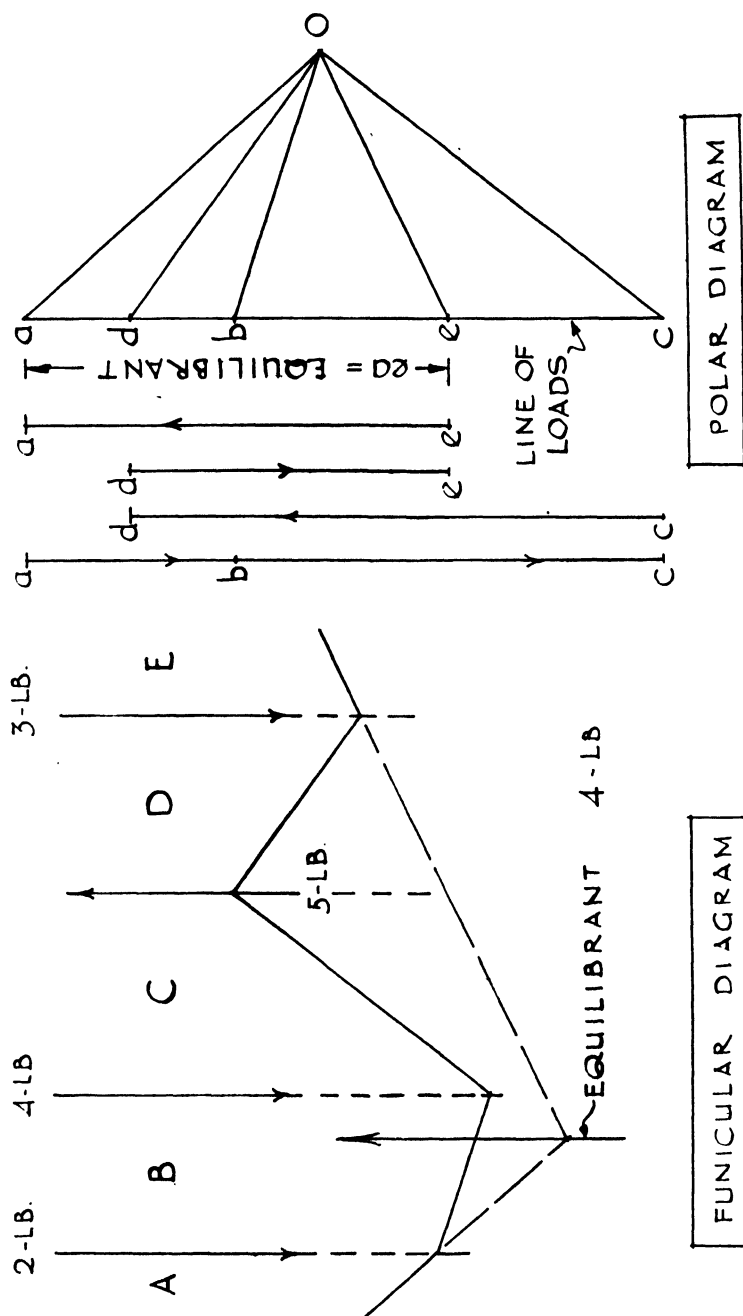


Fig. 137.—Equilibrium of Parallel Forces—Example 2.

Fig. 138 shows a force  $W$  acting vertically downwards. Considered in relation to the point  $A$  its effect is to tend to produce rotation or turning. This turning effect is called the *moment* of the force about the point. The same force has moments about other points, in fact about all points which do not lie in its line of action, but it is never necessary to consider more than one point at once.

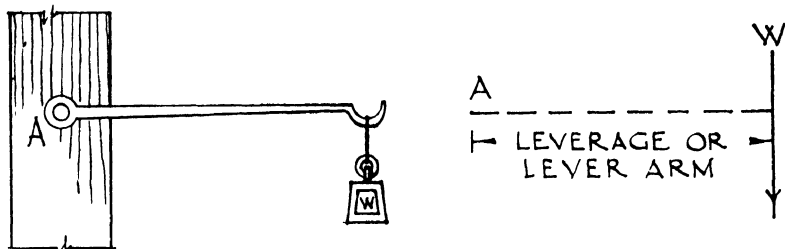


FIG. 138.—To Illustrate a Moment.

The amount of this moment is expressed as the *product* of the force and the leverage, and since the units involved are those of force and distance the units of moments are *inch-lb.*, *inch-tons*, *ft.-lb.*, *ft.-tons*, etc. For instance if the force shown in Fig. 138 were 4-lb. and the leverage 2-ft. the moment would be 8 ft.-lb. The leverage is the *perpendicular*, or shortest, distance between the point in question and the line of action of the force. The point about which the force is considered is called the *moment-centre*, and the moments are referred to as *clockwise* and *anti-clockwise* in accordance with their direction of rotation.

In Fig. 139 we have three non-concurrent forces acting, and about the point shown their effects are :—

$$\text{Force A } 2\text{-lb.} \times 3\text{ ft.} = 6\text{ ft.-lb. Anti-clockwise.}$$

$$,, \text{ B } 4\text{-lb.} \times 3\cdot5\text{ ft.} = 14\text{ ft.-lb. } ,, \text{ } ,,$$

$$,, \text{ C } 4\text{-lb.} \times 5\text{ ft.} = 20\text{ ft.-lb. Clockwise.}$$

In this case the turning effects of forces A and B about the point are balanced by that of Force C, and we thus have a condition of equilibrium.

**THE PRINCIPLE OF MOMENTS.**—When a body is acted upon by a number of parallel forces they must balance if the body is to be in a state of equilibrium. Similarly, for equilibrium, the moments of these forces about any point must balance, and this applies also to forces which are not parallel. The *principle of moments*, which applies to all systems of co-planar forces, states :—*When a body is in equilibrium under the action of any number of forces acting in a plane, the sum of the moments of those forces about any point in the plane is zero.* By “sum” is meant the algebraic sum, calling the moments positive or negative (+ or −) according to their direction of rotation, clockwise or anti-clockwise.



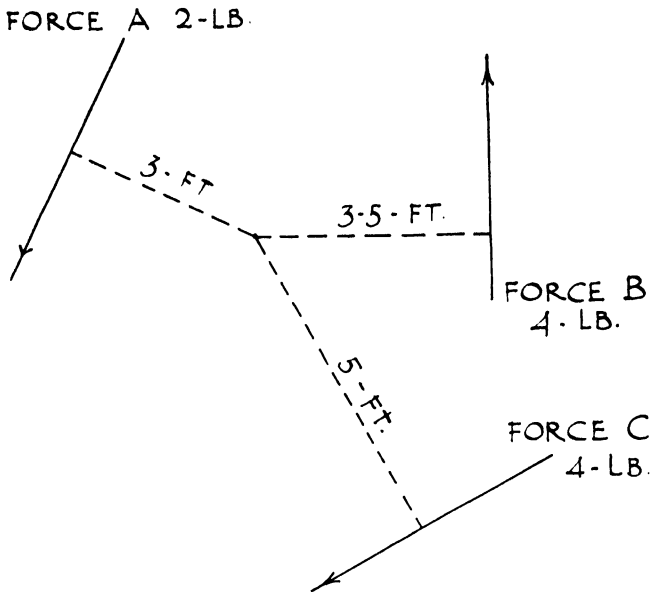


FIG. 139.—Equilibrium of Moments.

For vertical forces this can be demonstrated simply with the aid of the frame shown in Fig. 128.

**EXPERIMENT 114.**—To demonstrate the principle of moments.

Screw a metal eye into the top edge of a 36-in. boxwood rule at a point midway along its length and suspend it from a hook on the frame as in Fig. 140. The rod will be in equilibrium as shown by the fact that it maintains a horizontal position. Suspend a weight, say 3 lb., vertically below the point of suspension of the rod. This force is in line with the hook and so does not affect the equilibrium; incidentally it shows that the weight of the rule itself need not be considered, as it too does not affect equilibrium.

Now slide the weight along the rod to the left, say to a point 8-in. from the centre. The rule no longer remains horizontal but rotates anti-clockwise. To restore equilibrium hang another weight, say, 4 lb., on the rule to the right of the centre hook and slide it along until the rule hangs horizontally again. It will be found that it now hangs from a point 6-in. from the centre.

Anti-clockwise moment = 3 lb.  $\times$  8-in. = 2.4-in.-lb.

Clockwise moment = 4 lb.  $\times$  6-in. = 2.4-in.-lb.

The rule is in equilibrium because the moments of the two forces about the centre hook balance each other. Calling (merely for convenience) the clockwise moment positive and the anti-clockwise moment negative we have:—

$$- 2.4\text{-in.-lb.} + 2.4\text{-in.-lb.} = 0$$

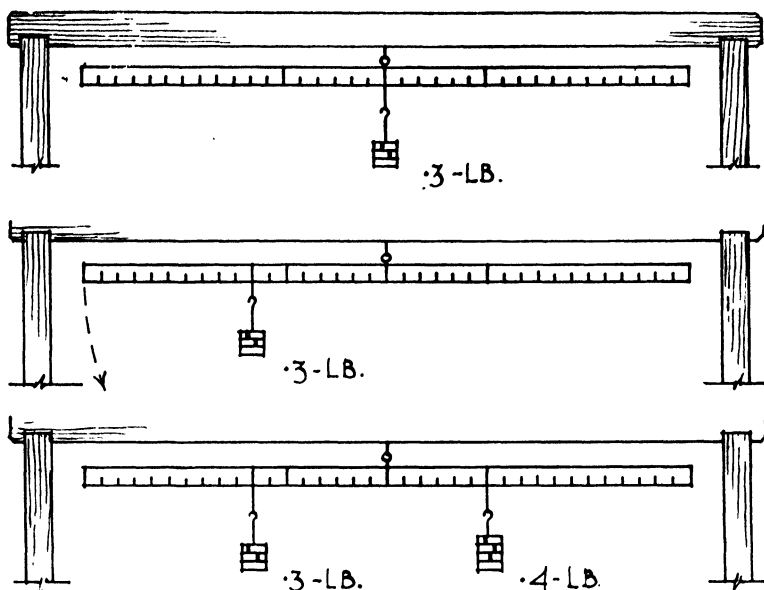


FIG. 140.—To Check the Principle of Moments.

The experiment should be continued with a larger number of weights ; for instance if weights are arranged as shown in Fig. 141 equilibrium will be represented by :—

$$\begin{aligned}\text{Anti-clockwise moments} &= (.2 \text{ lb.} \times 17\text{-in.}) + (.5 \text{ lb.} \times 6\text{-in.}) \\ &= 3.4 + 3.0 = \underline{6.4\text{-in.-lb.}}\end{aligned}$$

$$\begin{aligned}\text{Clockwise moments} &= (.4 \text{ lb.} \times 3\text{-in.}) + (.3 \text{ lb.} \times 12\text{-in.}) \\ &\quad + (.1 \text{ lb.} \times 16\text{-in.}) \\ &= 1.2 + 3.6 + 1.6 = \underline{6.4\text{-in.-lb.}}\end{aligned}$$

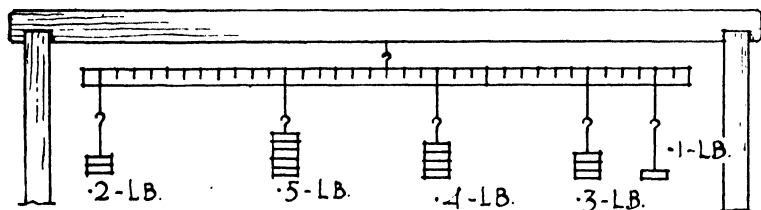


FIG. 141.—Example of Equilibrium of Moments.

### Exercises on Forces.

1. In the diagram at A in Fig. 142 the forces acting at the head of a jib crane are represented. The load being lifted by the rope is the only known force. Find the nature (tension or compression) and amount of the forces acting on the jib and the tie :—

- (a) When the jib is at 45 deg. ; and
- (b) When the jib is at 60 deg. to the horizontal.

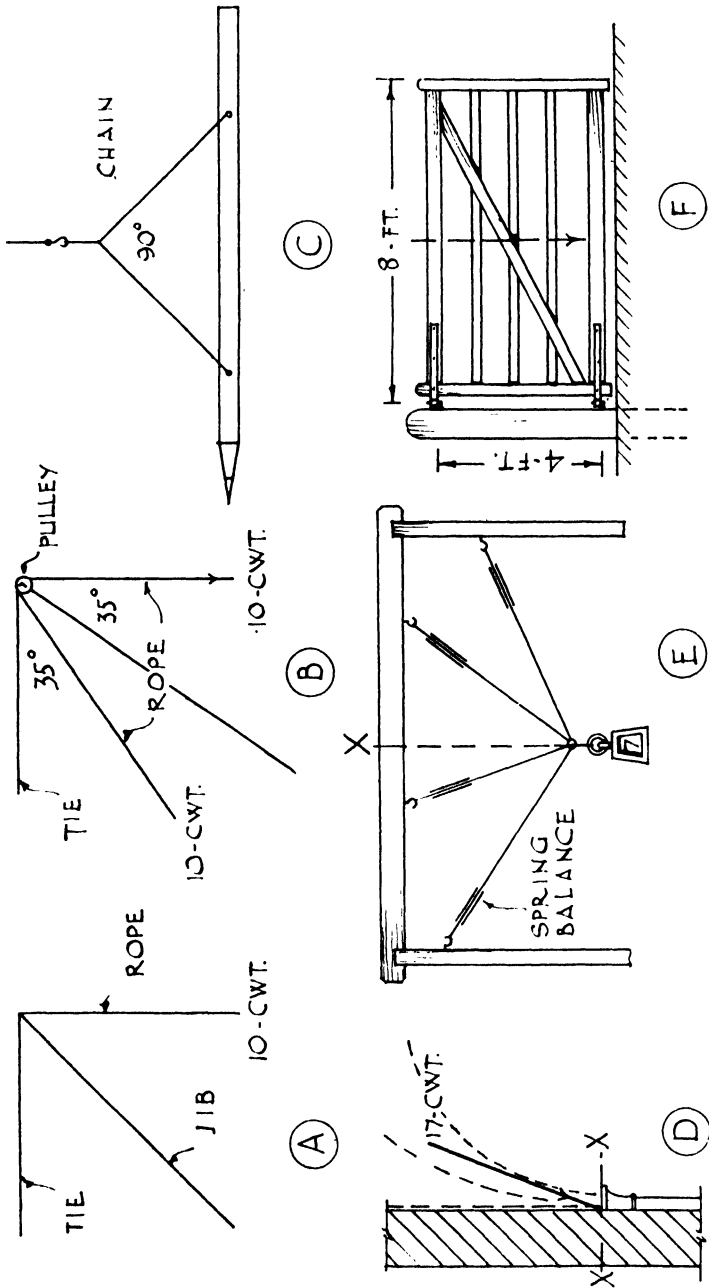


FIG. 142.—Diagrams for Exercises on p. 191.

2. At B is shown the head of a similar crane with pulley. Find the forces on the jib, tie and rope.
3. A concrete pile is being hoisted by means of a crane and chain as at C. If the pile weighs 1.25 tons what is the tension in the chain ?
4. The ribs of a stone vault, shown dotted at D, exert a thrust on a wall equivalent to a force of 17 cwts. acting at 60 deg. To what horizontal force applied at level X-X is this equivalent ?
5. Suspend a 7-lb. weight from four strings attached to spring balances as shown at E, measure the tensions and the angles between the strings, and then find the vertical and horizontal components of each force. Set these down in the form of a table to show that the sum of the four vertical components equals 7-lb. and the sum of the horizontal components to the left of line X equals the sum of those of the forces to the right of X.
6. At F is shown a gate weighing 120-lb. hung to a post by band hinges. Assuming that the pull on the upper hook is horizontal, determine the direction and amount of the thrust on the lower hook. (Assume the weight of the gate to act through its centre as shown by the dotted line.)

## 5. COUPLES.

A couple consists of two equal forces acting parallel and opposite to each other. Such a pair of forces tends to cause rotation when applied to a body and thus produces a moment, clockwise or anti-clockwise. Fig. 143 illustrates a couple, the forces being of 4-lb. each and acting 2-ft. apart.

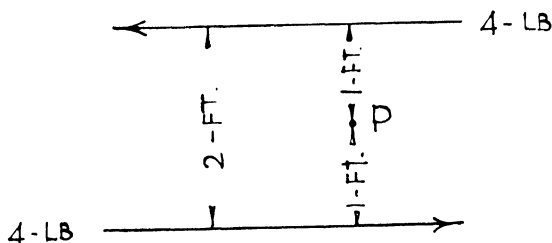


FIG. 143.—A Couple.

The magnitude of a couple is the amount of one of the forces multiplied by its perpendicular distance from the other. The magnitude of the couple shown in Fig. 143 is thus  $4 \text{ lb.} \times 2 \text{ ft.} = 8 \text{ ft.-lb.}$  (anti-clockwise). Its magnitude may also be considered as the moment of each force about a point midway between them. The moment of the couple in Fig. 143 is clearly  $(4 \text{ lb.} \times 1 \text{ ft.}) + (4 \text{ lb.} \times 1 \text{ ft.}) = 8 \text{ ft.-lb.}$  as before.

But the effect of the couple is unaltered whatever point is taken as moment centre. Thus, in Fig. 144 about point P the moment is  $(4 \text{ lb.} \times 3.5 \text{ ft.})$  anti-clockwise —  $(4 \text{ lb.} \times 1.5 \text{ ft.})$  clockwise =  $14 - 6 = 8 \text{ ft.-lb.}$  A couple may thus act in any position in the same plane without any change in its effect. Further, if a body is acted upon by

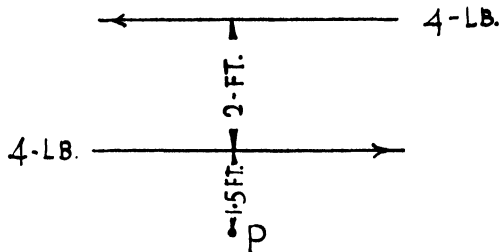


FIG. 144.—Couple unaffected by Position of Moment-Centre.

any two couples equal in magnitude but opposite in effect it will be in equilibrium. In Fig. 145 we have two couples of equal amount but opposite effect. Their resultant moment about any point P should therefore be zero. Let us see whether such is the case. Taking moments about point P we have :—

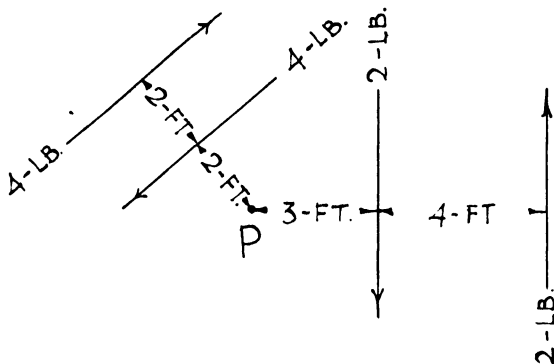


FIG. 145.—Equilibrium of Couples.

Clockwise moments	$4 \text{ lb.} \times 4 \text{ ft.} = 16 \text{ ft.-lb.}$
	$2 \text{ lb.} \times 3 \text{ ft.} = 6 \text{ ft.-lb.}$
Total clockwise moment	<u><u>22 ft.-lb.</u></u>
Anti-clockwise moments	$4 \text{ lb.} \times 2 \text{ ft.} = 8 \text{ ft.-lb.}$
	$2 \text{ lb.} \times 7 \text{ ft.} = 14 \text{ ft.-lb.}$
Total anti-clockwise moment	<u><u>22 ft.-lb.</u></u>

When we come to investigate the equilibrium of beams in a later chapter we shall find ourselves dealing with couples.

## STRESS AND STRAIN

1. *Stresses in Structural Members.*
  - (a) *Simple Stresses.*
  - (b) *Compound Stresses.*
2. *Strain and Elasticity.*
3. *Simple Testing for Strength.*
  - (a) *Simple Tension.*
  - (b) *Simple Compression.*
  - (c) *Direct Shear*
  - (d) *Bending.*

## 1. STRESSES IN STRUCTURAL MEMBERS.

We have already (page 170) defined stress as an internal force produced in the "fibres" of a material by the action of external force applied to it. We have seen that the equilibrium of a body depends upon the balance of the moments of forces acting upon it. It also depends upon the ability of the material of which the body is composed to withstand the stresses produced. In the next chapter we shall discuss rather fully the case of one of the commonest structural members, the beam; for the present we must investigate the stresses which maintain equilibrium with the applied forces up to the point of failure.

**Simple Stresses. Tension and Compression.**—If a piece of material such as a bar is subjected to a pulling force acting along its axis, as in Fig. 146, it is under tensile stress or tension, and at any cross section X—X this stress is distributed uniformly over the cross-sectional area as indicated by the small arrows. The amount of stress acting at each unit of area is called the *intensity of stress*, denoted " $f$ ", and the total stress at the section is the intensity of stress multiplied by the area over which it is acting, *i.e.* the cross-sectional area, denoted " $A$ ." The total stress is equal in amount to the total applied force  $W$ , and we may therefore say :—

$$W = f \times A$$

which we may, if required, transpose to give :—

$$A = \frac{W}{f}$$

$$\text{and } f = \frac{W}{A}$$

The same reasoning applies also to a body subjected to compressive force and thus under compressive stress. The intensity of stress is sometimes symbolized " $f_t$ " for tension and " $f_c$ " for compression, but

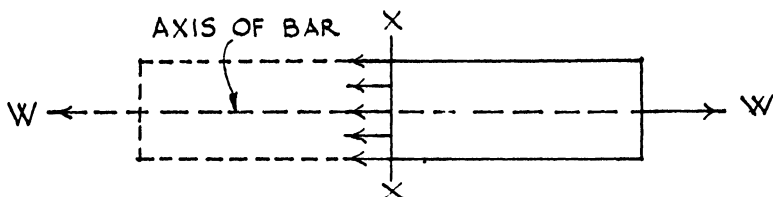


FIG. 146.—Distribution of Stress over a Section.

the formulæ are otherwise identical and as we know whether we are dealing with tension or compression in any particular case it is unnecessary to complicate matters by having two formulæ which really mean the same.

To return to Fig. 146, if the force  $W$  is great enough the bar will stretch (see Fig. 147, A) and ultimately fail by tearing. In the case of compression the body will shorten (as at B) and fail by crushing.

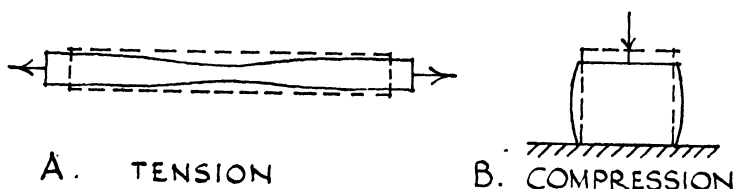


FIG. 147.—Effects of Tensile and Compressive Stress.

The minimum applied force necessary to cause failure is called the *failing* or *ultimate load*, and the intensity of stress at the point of failure is called the *failing* or *ultimate stress*.

**FACTOR OF SAFETY.**—We do not, for obvious reasons, permit materials to be stressed up to the point of failure, or even to a point near to it. So many factors are involved in practice that it is necessary to adopt *working* or *safe stresses*, corresponding to *working* or *safe loads*. These are the stresses and loads worked to in the designing of structural work and are based upon the ultimate stresses and loads by adopting a suitable fraction of the known ultimate values. This fraction is called the *factor of safety*; thus, if a material is known to fail at a stress of 12 tons per sq. in. and we arrange to stress it up to not more than 4 tons per sq. in. we are using a factor of safety of  $1/3$ . It is customary, however, to express it :—

$$\text{Factor of Safety (F.S.)} = \frac{\text{Ultimate stress}}{\text{Working stress}}$$

in the present instance  $\text{F.S.} = 3$ .

Some building materials are well adapted to resist tension but are not so suitable for compression, others excellent under compression are useless under tension. We therefore find that materials are normally used for such purposes and in such positions that they are utilized to the best advantage from the standpoint of resisting stresses. Thus brickwork,

stone, concrete, are normally used for walls, piers, arches, etc., where there is little chance of tension developing, for all these materials are weak in tension. Timber is strong under compression, but it is much stronger under tension, so that it is seldom used for withstanding simple compression. If, however, a member has to withstand both kinds of stress, as happens in the case of beams, long posts, etc., timber is a suitable material. For members taking tension only, such as tie bars or hangers, steel is the obvious material owing to its great strength in tension.

Table 11 gives the strengths of some common building materials together with the usual factors of safety. These will be seen to vary considerably with different materials. Some of the reasons for this will be enumerated.

The actual stresses reached may be higher than calculated for because conditions of loading are never known exactly, also it sometimes happens that a structure originally designed for one purpose may at a later date be used for a different purpose and thereby be loaded excessively. Other assumptions that have to be made for the purpose of design may also not be in exact accordance with practice. Materials differ in their reliability and uniformity; timber and other natural materials vary enormously in strength, as much in some cases as 100 per cent., and a high factor of safety is therefore necessary. Steel, which is manufactured to rigid specifications, is a far more reliable material and the factor of safety may thus be much lower.

TABLE 11.

STRESSES IN COMMON BUILDING MATERIALS. (TONS PER SQ. IN.)

<i>Material</i>	<i>Failing Stress</i>			<i>Working Stress</i>			<i>F.S. (Appr)</i>
	<i>Ten</i>	<i>Shear</i>	<i>Com.</i>	<i>Ten</i>	<i>Shear</i>	<i>Com.</i>	
Cast Iron .. ..	9	9	48	1.5	1.5	8	6
Wrought Iron ..	22	16	20	4.5	3	4	5
Mild Steel .. ..	32	24	32	8	6	8	4
Deal (Av.) .. ..	4	.2*	2.5	.5	—	.33	8†
Eng. Oak (Av.) ..	6	.4*	4	.75	—	.5	8†
Pitch Pine (Av.) ..	4	.33*	3	.5	—	.33	8†
1 : 2 : 4 Concrete (Av.)	—	—	2	—	—	.25 to .5	4 to 8
Red brickwork (Av.) in P.C. mortar ..	—	—	.5 to .75	—	—	.063 to .1	8
Blue ditto (Av.) ..	—	—	.75 to 1	—	—	.1 to .125	8
Granite ditto ..	—	—	1	—	—	.1	10
Sandstone ditto ..	—	—	.5	—	—	.05	10
Limestone ditto ..	—	—	.33	—	—	.033	10

\* = Shear along grain.

† F.S. may be reduced for temporary work.



With bricks and stones, very strong as units, we lose a great deal of their strength when we build them up with mortar, for the lower strength of the mortar affects that of the piece of construction. In the case of mild steel and wrought iron the elastic properties of the material affect the margin of safety for, although they withstand very high stresses before failing by fracture they "flow" or become permanently distorted long before the failing stresses are reached.

The type of construction also affects the suitability of a factor of safety; for instance whilst a F.S. of 4 may be satisfactory for mild steel when used as simple beam sections, ties, etc., lower working stresses may be advisable for work which is fabricated or "built-up," such as riveted girders, for here the human element is involved and cutting, riveting, etc., may be imperfectly done. Working stresses of 6-7 tons per sq. in. are often used in such cases. The position and subsequent accessibility of the work are other factors affecting the choice of working stresses; brickwork below ground level, concrete under water or steelwork in box section girders are examples.

Lastly, the factor of safety chosen must also take into account the nature of the loading to which the structure will be subjected. A *dead load* is one which is applied gradually and which afterwards remains constant; the weight of the construction itself is an example of this type of load. A *superimposed load* is one which is applied to the structure, and may be a *static load* such as the weight of furniture, etc. on the floor of a building, or it may be a *live load* such as the rolling of vehicles across a bridge, wind pressure on a tall building or the weight of lift mechanism supported on a beam. In buildings, as distinct from bridges and similar structures, the loads allowed for are the dead loads plus static superimposed loads. In the comparatively rare instances where live loads are encountered in buildings they are not considerable and for the purpose of calculation the actual live load is converted into an approximately equivalent static load.

The ultimate stress of any material is affected by the nature of the loading. A mild steel which fractures at a stress (tension or compression) of 32 tons per sq. in. when tested direct to destruction may be expected to fail at little over half this stress when the load is applied and removed continuously for a lengthy period. If it is subjected to continuously alternating tension *and* compression it may fail at no more than 11 tons per sq. in.

**SIMPLE DESIGN IN TENSION AND COMPRESSION.**—We may now proceed to work out a few examples, utilizing the formula given on page 195 and Table 11.

**EXAMPLE.**—A wrought iron tie rod in a roof is  $1\frac{1}{4}$ -in. diameter and receives a pull of 5.5 tons. What is the intensity of stress in the rod ?  
 Sectional area of  $1\frac{1}{4}$ -in. rod = 1.227 sq. in.

$$f = \frac{W}{A} = \frac{5.5}{1.227} = 4.48 \text{ tons per sq. in. } \underline{\text{Ans.}}$$

**EXAMPLE.**—A flat bar of mild steel is proposed for a hanger to sustain a load of 8 tons. Design a suitable section.

As the hanger will be connected to steelwork at its extremities by means of rivets its width should be at least 2-in. The problem then resolves itself into finding the necessary thickness.

$$A = \frac{W}{f} = \frac{8}{8} = 1 \text{ sq. in.}$$

$$\text{Thickness} = \frac{\text{Area}}{\text{Width}} = \frac{1 \text{ sq. in.}}{2 \text{ in.}} = \frac{1}{2} \text{-in.}$$

A suitable section is therefore 2-in.  $\times$   $\frac{1}{2}$ -in. Ans.

**EXAMPLE.**—A brick pier is to be built on soil which has a safe bearing pressure of 3 tons per sq. ft. The total inclusive load is 27 tons ; what area of footing is required ?

$$A = \frac{W}{f} = \frac{27}{3} = 9 \text{ sq. ft., say 3 ft. square. } \underline{\text{Ans.}}$$

**EXAMPLE.**—The end of a 12-in.  $\times$  6-in. steel beam transmits a pressure of 2 tons on to a stone pad. If the ultimate strength of the stone is 1,000-lb. per sq. in. what is the minimum length of bearing required ? Use a F.S. of 10.

$$A = \frac{W}{f} = \frac{4,480 \text{ lb.}}{100 \text{-lb. sq. in.}} = 44.8 \text{ sq. in.}$$

Width of bearing = 6-in.

$$\text{Therefore Length of bearing} = \frac{\text{Area}}{\text{Width}} = \frac{44.8 \text{ sq. in.}}{6 \text{ in.}} = 7\frac{1}{2} \text{-in. } \underline{\text{Ans.}}$$

**DIRECT SHEAR.**—Tension and compression are simple stresses. Certain other kinds of stress are more complex, including *shear*, but there are cases in which shearing stress occurs in a simple way. We therefore prefer the term “direct shear” to describe this rather than “simple shear.” Shearing stress occurs when a material is subjected to opposite forces not in the same line of action, and failure is by the sliding of one plane across an adjacent plane as in Fig. 148.

Members may be designed to resist this direct shearing stress by the direct stress formula given on page 195.

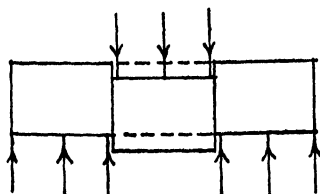


FIG. 148.—Shearing Stress.

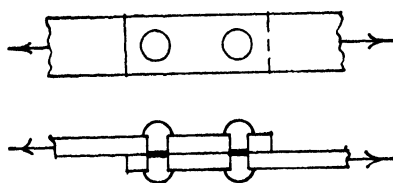


FIG. 149.—Example of Direct Shear—1.

**EXAMPLE.**—Two mild steel flat bars are connected by two 1-in. diameter steel rivets as indicated in Fig. 149. What is the working strength of the joint ?

The shank of each rivet is subjected to a shearing stress across the plane indicated by thicker lines in the diagram.

Sectional area of 1-in. rivet =  $\pi \times .5^2 = .7854$  sq. in.

$$W = f \times A$$

$$= 6 \text{ (from table)} \times 2 \times .7854 = \underline{9.42 \text{ tons. Ans.}}$$

**EXAMPLE.**—Fig. 150 shows a diagrammatic detail at the foot of a built-up steel roof truss. The horizontal tie is composed of a pair of steel flat bars connected to the gusset plate by two 1-in. diameter rivets. What is the working strength of the joint ?

In this case each rivet is subjected to shear across *two* planes, as indicated by thicker lines. The strength of each rivet is thus twice that of the same diameter rivet used in the previous example.

$$W = f \times A = 6 \times 4 \times .7854 = \underline{18.85 \text{ tons. Ans.}}$$

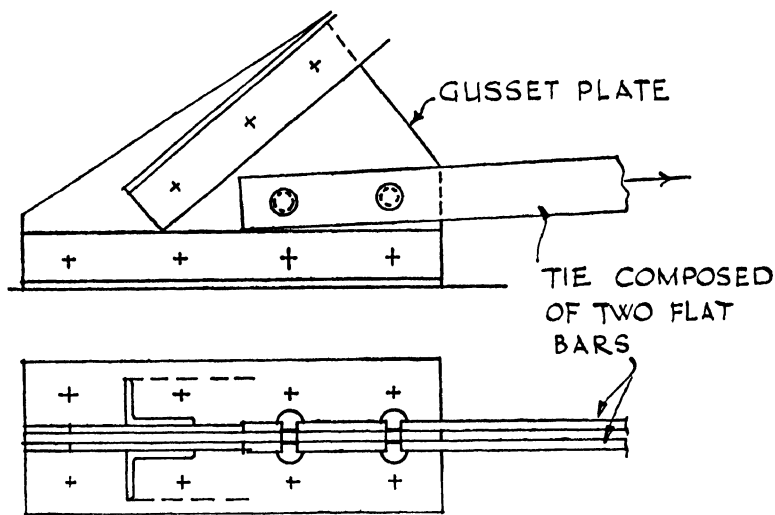


FIG. 150.—Example of Direct Shear—2.

Note that in these two examples the answers give the working strength of the rivets in shear. The section of the ties has not formed part of the problems but would have to be considered in practice ; no matter what the strength of the joint, if the member itself is insufficiently strong the structure would fail. Another practical point which has not been considered is the question of the rigidity of the gusset plate ; if this is too thin it may fail by the rivet shanks tearing through it before the strength of the rivets has been reached.

Rivets stressed across one plane as in Fig. 149 are said to be in *single shear*, whilst those stressed across two planes are in *double shear*. It is not usual in building work for rivets to be stressed across more than two planes. For instance if several bars come together as in Fig. 151,

A and B, the rivet is only in single or double shear respectively, as shown by the thick lines.

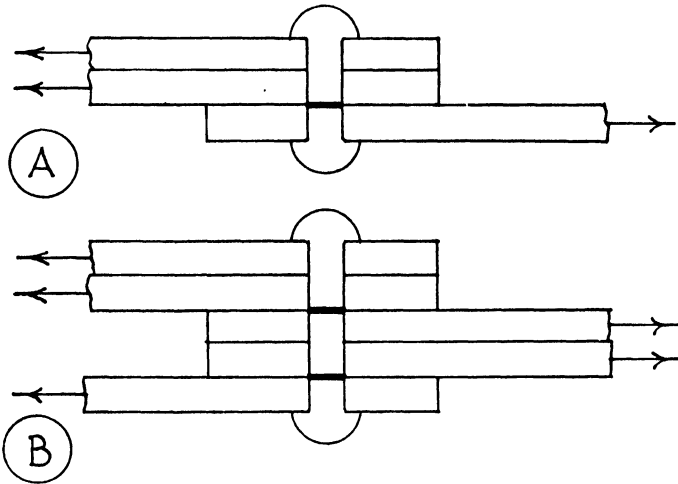


FIG. 151.—Single and Double Shear.

**EXAMPLE.**—Fig. 152 illustrates a “tension” joint in timber in which the trimmer joist is held tightly to the trimming joist by means of a tusked tenon and wedge. If the wedge is driven too tightly the tusk may fail by shearing along the grain as shown by the shading. This is the

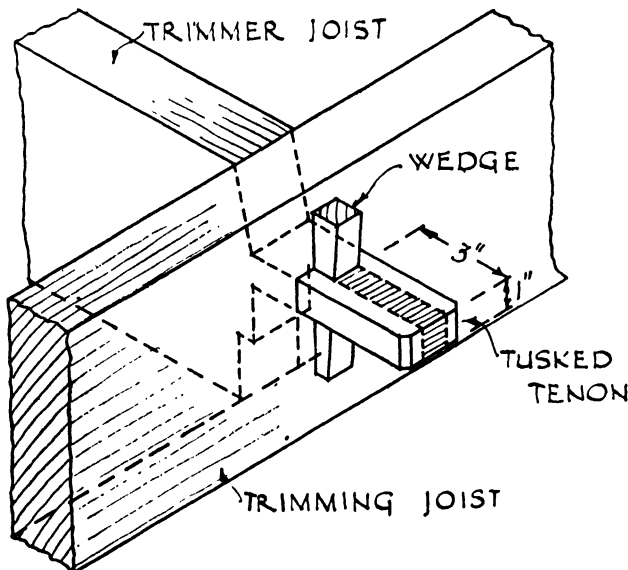


FIG. 152.—Shear Stress in a Tusked Tenon Joint.

reason why the tusk should project for a considerable distance. What is the maximum shearing force which may be exerted by the wedge ?

The tusk is tending to shear along two planes, each 1-in. deep and 3-in. long, the total area being

$$2 (3\text{-in.} \times 1\text{-in.}) = 6 \text{ sq. in.}$$

$$W = f \times A = .2 \times 6 = 1.2 \text{ tons.}$$

This is the failing load, and using the F.S. of 8, the maximum safe load would be  $\frac{1.2}{8} = .15 \text{ tons.}$  *Ans.*

A force of this amount is very easily produced in the process of driving a wedge, so that the importance of not over-tightening such a joint will be appreciated, as the tusk may be stressed near to failing point and subsequently fail by accident, in which case the whole purpose of the construction is defeated.

**Compound Stresses.**—Compound stresses are stresses other than simple tension and compression and direct shear. The principal ones occur in bending (transverse stress) and twisting (torsional stress). The latter calls for little explanation because it seldom occurs in problems of statics. It is really a special form of shearing stress. Suppose we have a steel shaft free to rotate in bearings and carrying a heavy flywheel or similar load and we then rotate the whole by turning force applied to the shaft. It will be clear that in overcoming the inertia of the flywheel the turning force tends to twist the shaft, in fact if the force is applied suddenly the shaft may possibly fracture by twisting before the flywheel has commenced to move. This type of stress is called *torsion*, and although many instances in connection with machinery are apparent the number of instances in which it can occur in a building is very limited ; when it does occur it is usually accidental and in conjunction with other stresses, such as in a narrow beam twisting under excessive loading. Bending stress, on the other hand, is perhaps the commonest stress met with in Building.

**TRANSVERSE STRESS.**—When a body is subjected to forces which cause bending it is under a stress called *bending* or *transverse stress*. Referring to Fig. 153 it will be seen that the originally straight body has

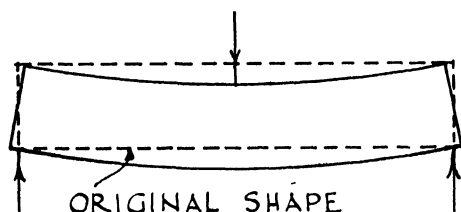


FIG. 153.—Transverse Stress.

become curved, concave on one side (in this instance the upper side) and convex on the opposite side. The concave side of the body has become shorter, and the convex side longer, than the original length. This may

be seen very clearly if a rubber eraser, having lettering or a pattern on the face, be bent between finger and thumb, first one way and then the other. The concave side of the body is obviously stressed in compression and the convex side in tension.

Transverse stress is thus a combination of tension and compression produced at the same time by the action of forces on a body. From what has already been said about shearing stress it is obvious, from the nature of the forces which produce bending, that shear is also produced. Most cases of bending are accompanied by shear in this way but it is possible, in laboratory work, to produce pure bending—without any shear stress—as will be seen later. (See page 255.)

Whilst such items as columns, walls, etc. are sometimes called upon to resist transverse stresses the beam is the member most directly affected, and these matters form the subject of the next chapter.

**SHEAR STRESS.**—As has been indicated, shearing stress, apart from direct shear, occurs as a compound stress usually in association with transverse stress. This question, too, is left over until we deal with the beam.

## 2. STRAIN AND ELASTICITY.

On page 169 we referred to the deformation of a body as “strain.” Strains are of various kinds and are named according to the kind of stress; thus tensile stress is accompanied by tensile strain (stretching, elongation or extension), compressive stress by compressive strain (shortening or contraction.)

**STRAIN.**—It now becomes necessary to define Strain more precisely. Let us take tensile strain as an example. Fig. 154 illustrates a bar of material subjected to tensile force. Its original length is 10-in. and it stretches to 11-in. The strain is therefore 1-in. But other specimens may be less, or more, than 10-in. long. It is therefore convenient to express the strain as elongation (or shortening in the case of compression) *per unit of length*.

Strain therefore =  $\frac{\text{Elongation (or shortening)}}{\text{Original length}}$  and is therefore a ratio.

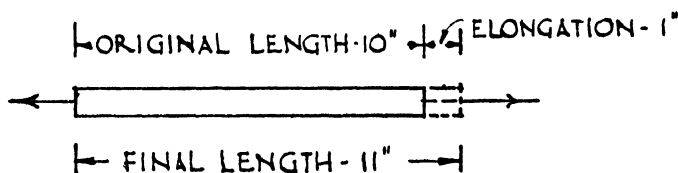


FIG. 154.—Tensile Strain.

**ELASTICITY.**—With most materials the strain resulting from stress (up to a certain point) disappears when the stress is released. In other words, on removing the load the body regains its exact original length. If a greater load is applied and a higher stress produced the body does not go quite back to its former length ; it finishes longer (in the case of tension) than originally, in other words the strain does not disappear. This is a permanent strain called *permanent set*, and the stress at which the material begins to “ flow ” (when the body would just fail to regain its original length) is called the *elastic limit*. *Elasticity* is the name given to the property of permitting strain to disappear on removal of stress.

No material is perfectly elastic, or to put it another way all materials have a certain elastic limit. Wrought iron and mild steel are elastic only up to a point roughly half way to breaking point ; they then flow or become plastic for an appreciable time before fracture occurs. The total elongation may be 20 per cent. Such materials are said to be *ductile*. Timber has an appreciable plastic stage in compression but not in tension. Glass is one of the most elastic materials, its elasticity being perfect almost to the point of fracture. Its elongation is negligible and it is therefore said to be *brittle*. Brick, stone, concrete and cast iron are brittle, not being perfectly elastic at any state of stress, but are sufficiently so to permit of its assumption, within the particular limits, for the purpose of design in these materials.

Referring to Experiment 108, page 166, and the graph, Fig. 112, we see an example of strains within the elastic limit of the rubber, and note that the strain and the load (and consequently the stress) increase proportionately. We can show that an identical effect is produced by loading a metal specimen say an iron or steel wire.

**EXPERIMENT 115.**—To investigate the elasticity of steel.

Metal in the form of thin wire is very suitable for a general investigation of this kind as the length tested may be considerable, and the strains of such magnitude as to be capable of direct measurement with a steel rule or a vernier scale. Secure the wire at one end to the end of a bench or table and apply loads to the other end by running the wire over a stout pulley. Arrange as great a length as possible, by using two tables it may be considerable, and interpose at A (Fig. 155) any suitable object to act as an index. Apply first a small weight, say the hanger of a set of large disc weights, to stretch the wire taut, and then apply the loads in increments of say 2-lb., noting the elongation by placing a steel rule on the table under the index. Continue until the wire shows obvious signs of overstrain, still noting the elongations, and set down the results, afterwards plotting them in the form of a graph.

The wire should then be discarded, or used for some other purpose, as it cannot be used again for a similar experiment.

From the resulting graph (Fig. 156) it is seen that up to the elastic limit the graph is a straight line as in the case of the rubber cord, but that after this point the elongation increases out of proportion to the load, producing a curved portion on the graph.

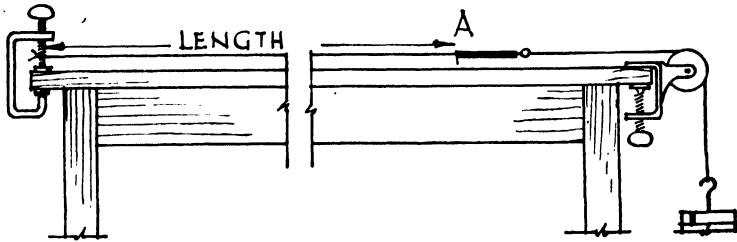


FIG. 155.—To Show the Relationship between Load and Extension of Steel Wire.

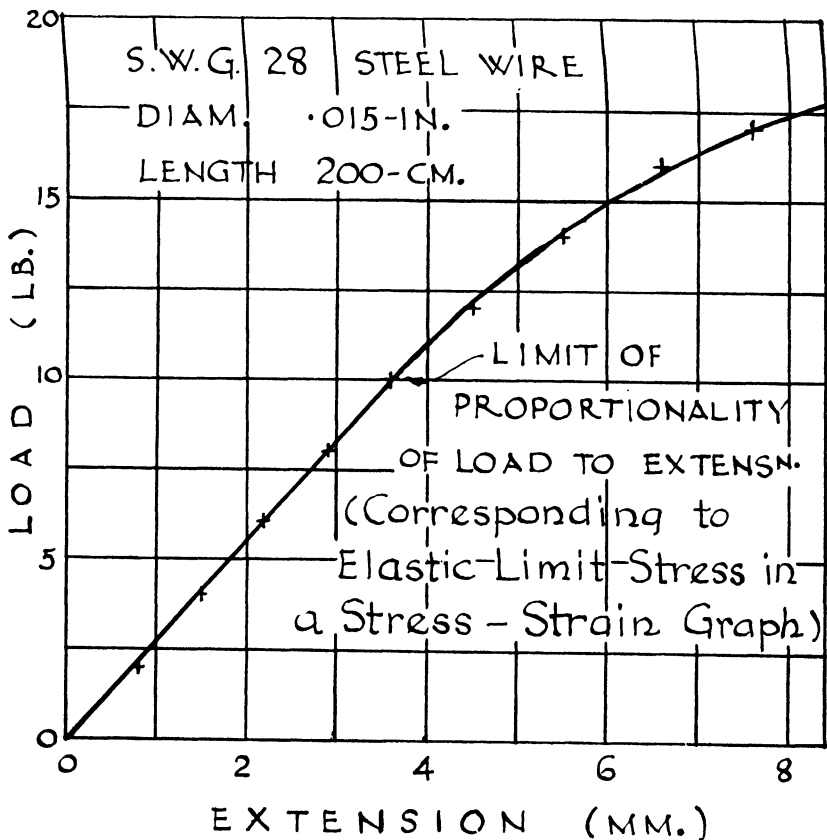


FIG. 156.—Graph showing Limit of Proportionality of Load to Extension of Steel Wire.



The proportionality of elongation to load, or the equivalent strain to stress, as shown by the straight portion of the graph, is known as *Hooke's Law*. The statement is :—*Within the elastic limit of any material strain is proportional to stress.*

For any material this relation between stress and strain can be expressed thus :—

$$\text{Stress} = \text{Strain} \times \text{a constant.}$$

The constant is obviously different for different materials and is *the force required to stretch a bar of the material of unit sectional area to twice its original length, assuming the material to be perfectly elastic*, that is, assuming this amount of strain to be possible within its elastic limit.

This constant is known as *Young's Modulus* or the *Modulus of Elasticity*, and is symbolized E. Another way of expressing this constant is :—

$$E = \frac{\text{Stress}}{\text{Strain}}$$

from which we get :—

$$\begin{aligned} \text{Stress} &= E \times \text{Strain} \\ \text{and Strain} &= \frac{\text{Stress}}{E} \end{aligned}$$

The value of Young's Modulus varies, for the same material, with the type of stress, but for tension and compression its values are approximately identical. Table 12 gives values for various structural materials.

TABLE 12.  
MODULUS OF ELASTICITY (E) OF MATERIALS.

Material	Value of E (approx.)	
	Tons per sq. in.	Lb. per sq. in.
Mild steel .. ..	13,500	30,000,000
Wrought iron .. ..	12,000	27,000,000
Softwood (av.) .. ..	580	1,300,000
Hardwood (av.) .. ..	650	1,450,000
Brickwork .. ..	650 to 1,300	1,450,000 to 3,000,000
Concrete .. ..	450 to 1,800	1,000,000 to 4,000,000

EXAMPLE.—A wrought iron bar 1 sq. in. in section and 10 ft. long takes a load of 1 ton in tension and stretches .01 in. What is the value of E ?

$$\text{Stress } f = \frac{W}{A} = \frac{1 \text{ ton}}{1 \text{ sq. in.}} = 1 \text{ ton per sq. in.}$$

Elongation of .01 in. is produced by stress of 1 ton per sq. in.

" " 120 in. " " " "

$$\frac{1 \times 120}{.01} = \underline{\underline{12,000 \text{ tons per sq. in. } \text{Ans.}}}$$

Alternatively :—

$$\text{Strain} = \frac{\text{Elongation}}{\text{Original length}} = \frac{.01}{120} = \frac{1}{12,000}$$

$$E = \frac{\text{Stress}}{\text{Strain}} = \frac{1 \times 12,000}{1} = \underline{12,000 \text{ tons per sq. in. Ans.}}$$

EXAMPLE.—A mild steel tie rod is 14 ft. long and 2-in. in diameter and is subjected to a force of 15 tons. How much does it lengthen under load ?

Sectional area of tie =  $\pi r^2 = \pi \text{ sq. in.}$

Load of 13,500 tons stretches 1 sq. in. rod 14 ft. = 168 in.

„ „ 13,500  $\times \pi$  tons „ „ „ „ 168 in.

„ „ 15 tons „ „ „ „ „  $\frac{168 \times 15}{13,500 \times \pi} = .06 \text{ in. Ans.}$

Alternatively :—

$$\text{Strain} = \frac{\text{Stress}}{E} = \frac{15}{\pi} \times \frac{1}{13,500} = .000354$$

$$\begin{aligned} \text{Elongation} &= \text{Strain} \times \text{Original length} \\ &= .000354 \times 168 = \underline{.06 \text{ in. Ans.}} \end{aligned}$$

PRINCIPAL STRAIN AND LATERAL STRAIN.—When an elastic material is under tensile stress the strain is one of elongation in the direction of the applied force. This should strictly be termed the longitudinal or *principal strain*, since it is always accompanied by a contraction or compressive strain at right-angles to it, called the *lateral strain*. Similarly, a principal strain of shortening due to compression is accompanied by lateral tension, which shows as bulging or dilatation. The lateral and principal strains are in a definite ratio called *Poisson's Ratio*, and its value is constant for each material but is different for different materials. Thus for concrete its value is .2, for glass .245, for steel .269, for rubber .5.

The strain resulting from simple stress is therefore not pure strain, but this fact is taken into account in Young's Modulus, since E is deduced empirically.

SIMPLE TESTING FOR STRENGTH.—Although the testing of building materials is beyond the scope of this volume we may at this stage describe a few simple tests which are easily carried out with the aid of a small testing machine. Testing machines are of many different types according to the purposes for which they are designed ; their capacities vary also from about 1 ton up to 500 tons or more. For elementary work of a general character a "universal" machine of 10 to 15 tons capacity is ideal and is the type most likely to be available. Such a machine may be arranged to apply loads by screws and gears, counterweight, or by oil pressure. The one illustrated diagrammatically in Fig. 157 is a 10-ton hydraulic machine capable of testing directly in tension, compression and bending. The chief points are :—

- (a) The oil chamber, which is connected by oil pipe to a hand pump with suction pipe and sump for oil.

- (b) The ram, which moves up and down by oil pressure.
- (c) The four columns and moving head, all attached to the ram and moving vertically with it.

The head accommodates the upper grip for tensile specimens.

- (d) The fixed cross-head, which has the lower tensile grip on top and the upper compression bearing block underneath, also sliding bearings for transverse test pieces such as beams.

On top of the ram may be fitted at will the lower compression bearing block or alternatively the centre transverse bearing block.

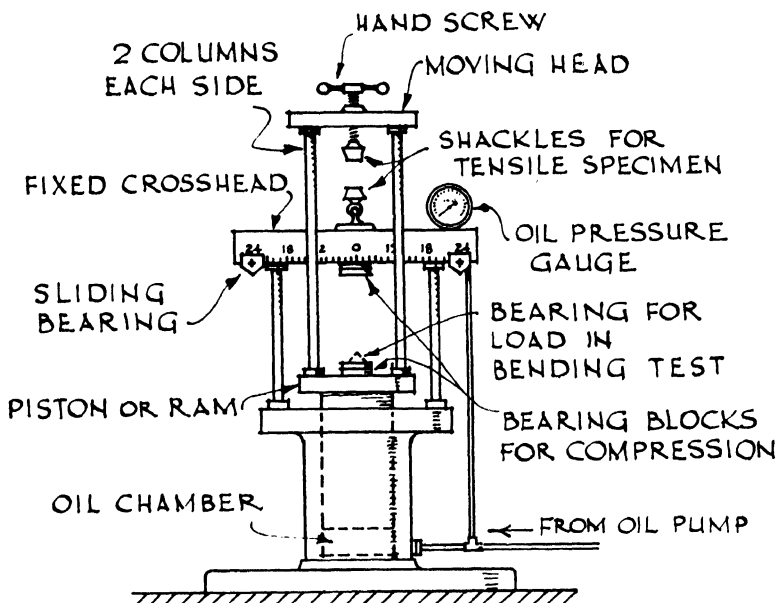


FIG. 157.—Ten-ton Hydraulic Testing Machine.

In use, the specimen is placed in position and the hand pump operated. This forces oil from the sump along the oil pipe to the oil chamber of the machine, whilst a branch pipe serves an oil-pressure gauge. The area of the end of the ram is 30 sq. in. and this multiplied by the intensity of oil pressure (lb. per sq. in.) gives the load on the specimen. The gauge gives the total load directly in tons, as well as the intensity of oil pressure in lb. per sq. in.

**TESTING FOR TENSILE STRENGTH.**—Tension tests are usual for metals and for cements and cement mortars. The latter, however, require a special machine as the shape of the specimen and the arrangement for holding it during the test are different. These will be described in the second volume. Timbers are also tested in tension, but special precautions are necessary.

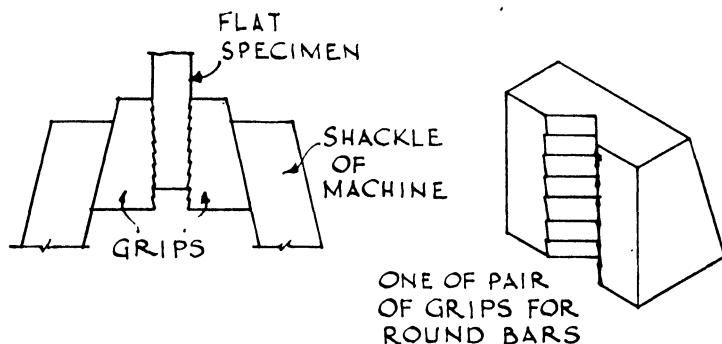


FIG. 158.—Method of Gripping Ends of Metal Specimens.

**EXPERIMENT 116.**—A simple tensile test for mild steel.

The most convenient type of specimen is a round bar or rod and it is held at the ends by special hard steel grips having serrations which "bite" into the specimen more firmly the greater the load applied. It is clear from this that if we use a bar of uniform diameter, say a length of ordinary rod cut from a long piece, it is likely to fracture at the ends where it is gripped rather than at some point between. To obviate this difficulty the ends of the test piece should be of larger diameter than the central portion. This is accomplished by turning the specimen in a lathe and finishing by grinding. To suit the capacity of our machine we may decide upon a diameter of  $\frac{3}{8}$ -in. which gives a sectional area of  $\cdot 1104$  sq. in. This is turned from a length of  $\frac{1}{4}$ -in. or  $\frac{3}{8}$ -in. diameter rod, and is shown in Fig. 159.

Measure off from the centre of the reduced diameter portion a distance of 3-in. each side and at each point make a fine punch mark as shown. Then fit the test piece into the machine and apply the load gradually. When the load has reached about  $1\frac{1}{2}$  tons measure with the dividers and steel rule the distance between the two marks. It will be found to be slightly longer than originally. Now release the load, again measure with the dividers and it will be found to have returned to its original length. We are obviously still within the elastic limit of the steel. Now work the pump again and continue to increase the load gradually, after about 3 tons watching the specimen carefully and applying the dividers to the marks from time to time. When the load has passed about 3 tons the surface of the specimen will appear to become roughened at a point somewhere near to the centre and it will be seen to be contracting to form a "waist." Continue the loading very gently when this occurs and watch for fracture to take place. In the case described this occurred at a load of 3.48 tons, giving an ultimate stress of 31.5 tons per sq. in.

The appearance of the fractured surfaces should be noted, and the two portions fitted together on the table and the distance between the two marks measured again. The elongation should be calculated as a percentage of the original length and will be found to be about 28 per cent. It naturally varies with the original length taken; if a length of 1-in. containing the fracture were taken the percentage would be much greater.

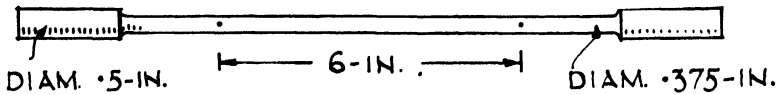


FIG. 159.—Tensile Specimen of Mild Steel.

If a similar test piece of cast iron can be obtained it should be tested in a similar manner, but the failing stress and elongation will of course be different. The elongation will be very much less owing to the less ductile nature of cast iron.

Timber specimens are more difficult to test in tension owing to the grips crushing the fibres and causing the specimen to split longitudinally. This also makes it difficult to maintain a direct pull and some bending usually occurs. In any event the results obtained with timber specimens of small cross-section are not representative and larger specimens are necessary, tested in a machine of greater capacity. Also to avoid the complications produced by crushing at the ends the specimens should be arranged with square shoulders as in Fig. 160 so that they need not be gripped. In this connection it must be remembered that the length *A* must be sufficient to prevent the shoulders from shearing off before the specimen fails by tension at the reduced cross section. Failing this, the ends of the specimen may be splayed to fit the taper of the shackles into which the steel grips are fitted. They would then be as in Fig. 161.

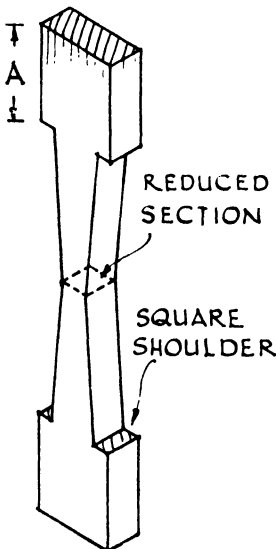


FIG. 160.—Tensile Specimen of Timber.

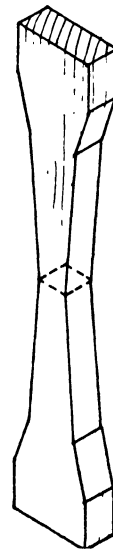


FIG. 161.—Alternative Shape for Timber Specimen.

**TESTING FOR CRUSHING STRENGTH.**—Specimens to be tested in compression should be short in relation to their breadth. The ideal specimen is a cube, or a cylinder whose height is little more than its diameter. It will thus be seen that with only a small machine available measurements of strain are not possible, except with strain measuring instruments. This type of work is beyond the scope of this first volume.

When a slender specimen is tested in compression it is found to fail at a lower load than does a short specimen having an identical sectional area. This is because bending stresses are induced in addition to simple compression; the greater the length or height the lower the failing load. This question also is one left over for the present although it is of interest to verify it roughly by crushing a number of timber specimens each, say, 1-in. square and having lengths of 1-in., 2-in., 3-in., etc. The following figures were obtained in this way:—

All specimens end-grain and 1-in. square.

Specimen A	..	Height 1-in.	Av. of 6.	4.91 tons.
„ B	..	„ 2-in.	„	4.7 „
„ C	..	„ 3-in.	„	4.35 „
„ D	..	„ 4-in.	„	3.17 „

In Experiment 48 (page 98) we applied compression tests to 2-in. cubes of cement mortar to ascertain their crushing strengths. If such specimens are tested at an early age they may be found to come within the capacity of the testing machine described, although those in question were tested in a 50-ton machine, and some similar 6-in. cubes in a 200-ton machine.

Cubes of red “rubber” brick may be prepared and tested on the small machine but other types of brick, besides metals and timber need a larger one for satisfactory tests in compression.

**TESTING IN DIRECT SHEAR.**—For the testing of timber the specimen may take the form somewhat similar to the tensile test piece shown in

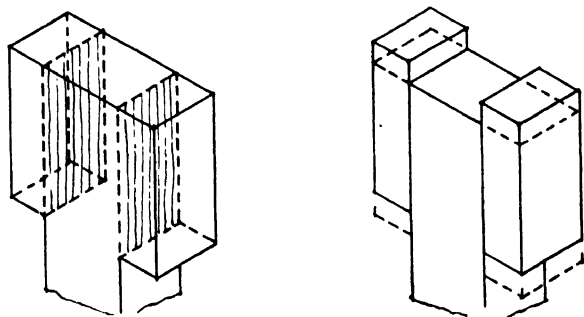


FIG. 162.—Shearing Test-Piece for Timber (by applied tension).

Fig. 160, if the machine can be adapted to hold the ends by the square shoulders. The test piece should however not be tapered and the length of the ends should be reduced so as to be certain that failure will be by shearing and not by tension. Fig. 162 shows the extent of the planes along which shearing would take place. Failing this, shearing along the grain may be arranged to take place by applied compression as indicated in Fig. 163.

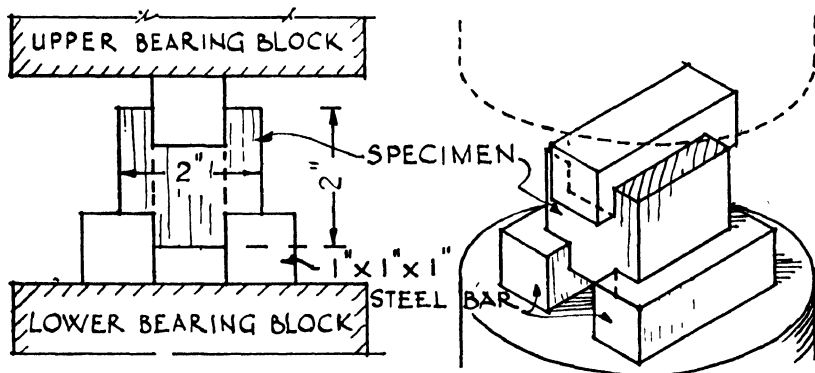


FIG. 163.—Shearing Test-Piece for Timber (by applied compression).

Round steel rod may be tested in shear as shown in Fig. 164. Each of the steel plates is a 3-in. length of 2-in.  $\times$   $\frac{1}{2}$ -in. flat bar with a  $\frac{1}{2}$ -in. (full) hole to take the test piece, which is a short length of  $\frac{1}{2}$ -in. rod. All three plates are identical but the centre one is reversed for the purpose of the test and the load applied through the compression bearing blocks of the machine.

In these rough methods of shear testing the specimen is subjected to double shear. Failure in single shear is more difficult to arrange as it requires special apparatus to hold the specimen.

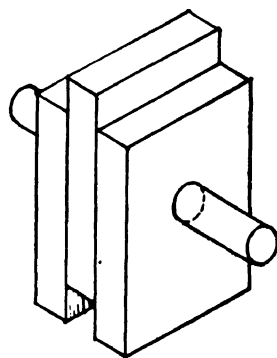


FIG. 164.—Scheme for Shear Test on Steel Rod.

**SIMPLE TRANSVERSE TESTING.**—Transverse testing is quite beyond the scope of this volume, but it will be of interest to carry out a series of simple bending tests on timber so as to give us data from which we may select a timber beam to suit given conditions.

The specimens are all 1-in. thick and may be cut from a  $1\frac{1}{4}$ -in. nominal straight grained red deal board planed down to a full 1-in. thickness. The sizes required are :—

No. 6 pieces 1-in. wide and 15-in. long.

No. 12 „ 2-in. „ „ 15-in. „

No. 6 „ 1-in. „ „ 27-in. „

Except for the length, which is only approximate, the dimensions are the finished dimensions and should be accurate. The specimens are to be tested as beams as follows :—

Specimens A	..	Breadth 1-in.	Depth 1-in.	Span 1-ft.
„ B	..	„ 2-in.	„ 1-in.	„ 1-ft.
„ C	..	„ 1-in.	„ 2-in.	„ 1-ft.
„ D	..	„ 1-in.	„ 1-in.	„ 2-ft.

**EXPERIMENT 117.**—To investigate the breaking strength of beams.

For the purpose of these tests the lower knife-edge bearing block is placed in position on the ram, the upper compression block removed, and the sliding bearings moved so that each occupies a position 6-in. from zero (the centre of the fixed cross-head of the machine). Their knife-edges are now 1-ft. apart, and that of the lower block corresponds to zero, so giving a central “ point ” load on the under-side of the beam. The beam is thus upside down as compared to conditions in practice but this is merely to suit the machine and does not affect the results.

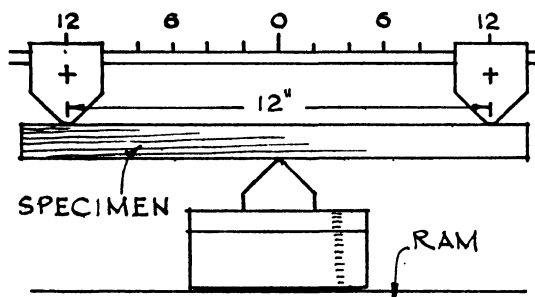


FIG. 165.—Transverse Test on Timber.

Specimen A is now inserted and the hand pump operated, and the ram raised, until the beam is held tightly in position but without appreciable load. Loading is now continued steadily and the beam is seen to bend upwards considerably, finally failing by tearing apart in the uppermost fibres. The load at the point of failure is carefully noted and recorded. The other specimens A are similarly broken and results recorded. Specimens B are placed in the machine with the 1-in. dimension as the depth and the 2-in. dimension as the breadth, and so on, according to the list above. For specimens D the sliding bearings are placed at 24-in. apart, or each 12-in. from centre.

Experimental results of these tests are given below, but other results may vary slightly from these, depending upon the type of timber, the straightness of the grain, freedom from knots or otherwise, its age, dryness and many other considerations.



## BREAKING STRENGTH OF TIMBER BEAMS. (lb.) Point loading.

Specimen A ..	450	450	420	510	450	420	Mean	450
„ B ..	870	930	840	840	900	930	„	885
„ C ..	1,800	1,740	1,590	1,560	1,620	1,500	„	1,555
„ D ..	210	240	270	210	270	270	„	245

If, a transverse testing machine is not available a compression machine may be used by arranging the beam supports on a deep section steel beam placed across the bottom plate of the machine as shown in Fig. 166. The loads should be applied by rollers consisting of short lengths of round steel bar.

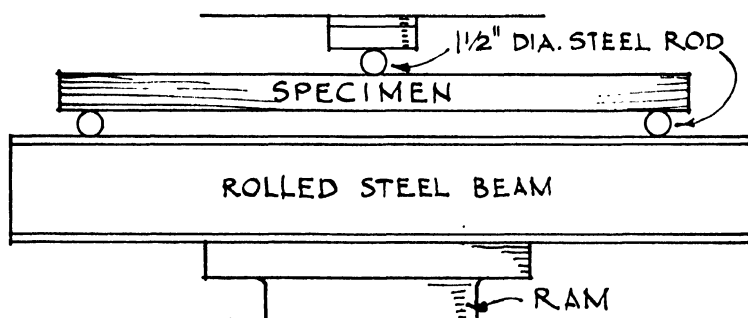


FIG. 166.—Transverse Testing in a Compression Testing Machine.

Let us now study carefully the results obtained. Taking specimen A as standard we find that by doubling the breadth we get roughly twice the strength; by doubling the depth we get something approaching four times the strength; by doubling the span we reduce the strength to approximately one-half. Allowing for experimental error, and remembering that the problem of shear stress affects each of the four cases in different degrees, we may say that the breaking strength of the beams varies :—

- (a) Directly as the breadth for given depth and span.
- (b) Directly as the square of the depth for given breadth and span.
- (c) Inversely as the span for given breadth and depth.

In other words the strength varies as  $\frac{b \times d^2}{l}$

where :— $b$  = breadth.

$d$  = depth.

$l$  = span.

As Specimen A has unit breadth and depth (1-in.) and unit span (1-ft.) we may take its strength as a constant  $C$  and say :—

$$\text{Central failing load} = \frac{C \times b \times d^2}{l}$$

$C$  for our red deal being 450-lb. or .2 tons.

Note that  $b$  and  $d$  are in inches, but  $l$  is in feet.

By substituting other values of breadth, depth and span we may therefore use the formula to determine, without experiment, the central failing load for beams of other dimensions, provided they are of the same type of timber. Further, by the use of the appropriate factor of safety, we can determine their central safe load. And, finally, by doubling the value of  $C$  (see Chapter XV) we can obtain the safe or working *uniformly distributed* load.

The value of  $C$  for any timber is obtained by breaking several beams 1-in.  $\times$  1-in.  $\times$  1-ft. span and taking the mean value. For stronger timbers than deal its value will be found to vary between .2 tons and .3 tons.

A few examples will illustrate the use of the formula.

**EXAMPLE.**—Find the central failing load on a deal beam 11-in. deep and 6-in. wide over a span of 12-ft.

$$\begin{aligned}\text{Central failing load} &= \frac{C b d^3}{l} = \frac{.2 \times 6 \times 11 \times 11}{12} \\ &= \underline{12.1 \text{ tons. } \textit{Ans.}}\end{aligned}$$

**EXAMPLE.**—A 9-in. wide deal lintel carries a brick wall over an opening 9-ft. wide. The total load is 4 tons. What is the minimum depth for the beam ? F.S. 8.

$$\text{Safe distributed load} = 4 \text{ tons.}$$

$$\text{,, Central ,,} = \frac{4}{2} = 2 \text{ tons.}$$

$$\begin{aligned}\text{Failing central load} &= 2 \times 8 = 16 \text{ tons.} \\ &= \frac{C b d^3}{l}\end{aligned}$$

$$\text{Therefore } d^3 = \frac{16 \times l}{C \times b} = \frac{16 \times 9}{.2 \times 9} = 80$$

$$\text{and } d = \sqrt[3]{80} = \underline{9\text{-in. nearly. } \textit{Ans.}}$$

In the last example the section is 9-in.  $\times$  9-in. This square cross-section is wasteful in normal circumstances but in the present case the 9-in. breadth is required for practical reasons—to carry the 9-in. wall. For beams having lateral support, such as strutted floor joists, the depth should be as great as possible and the breadth reduced to a minimum. For beams having no lateral support, such as binders and lintels, the most economical cross-section is one in which the depth is approximately twice the breadth. In the interests of economy there are also practical considerations to be taken into account. For instance if we calculate a suitable section to be 10-in.  $\times$  5-in. (50 sq. in.) it would be preferable to substitute a 9-in.  $\times$  6-in. (54 sq. in.) since, although slightly wasteful of timber it would be obtainable more readily as a market section, or, in the form of two 9-in.  $\times$  3-in. sections more readily still, and also at a cheaper rate according to the custom of the timber trade.

**Exercises.**

1. A block of granite is used as a foundation to take the thrust of an arch rib in a steel bridge. The bearing of the rib is 2-ft.  $\times$  3-ft. What is the maximum thrust that is permissible ? (*Ans.* 86.5 tons.)
2. The foot of a 9-in.  $\times$  9-in. oak post forming part of a timber-framed building bears at right-angles on a similar sill. It has a 3-in. square stub tenon joint. The load transmitted to the sill is 12 tons. Discuss the safety of the construction. (*Ans.* The compressive stress in the sill is  $\frac{1}{8}$  ton per sq. in. which is well within the safe stress for oak.)
3. A mild steel flat tie bar is  $2\frac{1}{2}$ -in.  $\times$   $\frac{3}{4}$ -in. in section and is lengthened by connecting to a similar bar with two cover plates and two 1-in. diameter rivets. It is tested to destruction. How does failure occur ?

**NOTE :** In calculating the strength of the bar in tension the reduced section, across rivet hole, must be taken.

(*Ans.* Strength of bar across rivet hole = 18 tons.

Strength of joint — two rivets in double shear = 18.85 tons.  
Failure would therefore be by tension in bar across one of the rivet holes.)

4. A deal test piece is of the type shown in Fig. 160. Its thickness is  $\frac{1}{2}$ -in. and the reduced section  $\frac{1}{2}$ -in.  $\times$   $\frac{1}{4}$ -in. What is the minimum length of shoulder A to ensure that failure will occur by tension ?  
(*Ans.* Using values in Table 11 ultimate strength in tension is approximately  $\frac{1}{2}$ -ton. To give this strength in shear A must be at least  $2\frac{1}{2}$ -in. and to produce failure by tension A must be more than  $2\frac{1}{2}$ -in.)
5. Find the strength in double shear of a  $\frac{3}{8}$ -in. diameter steel rivet. (*Ans.* 7.215 tons.)
6. A dwarf pier 10-in. square is 20-in. high. The material has a Modulus of Elasticity of 2,000,000 lb. per sq. in. Find the amount the pier shortens under a concentric load of 25 tons. (R.I.B.A. Inter.) (*Ans.* .0056-in.)
7. A steel bar is 2-in.  $\times$  2-in.  $\times$  20-ft. long. The elongation resulting from a tensile load of 32 tons is .1344-in. What is its Modulus of Elasticity ? (R.I.B.A. Inter.) (*Ans.* 14,286 tons per sq. in.)

## THE EQUILIBRIUM OF THE BEAM

1. *Reactions of Beams.*
2. *Bending Moments on Beams.*
3. *Shearing Stresses in Beams.*
4. *Resistance to Bending of Beams.*

## 1. REACTIONS OF BEAMS.

A beam is a member (or structure) whose length is usually great in proportion to its other dimensions, which is used for supporting loads over a clear space and which endures bending stresses in doing so. An arch also supports loads over a clear space but is so designed that no bending stress occurs, whereas a beam is designed purposely to be capable of resisting such stress.

A beam is thus a body acted upon by a number of forces, usually a horizontal body acted upon by vertical forces, and our previous study of parallel force systems applies to the case of the beam. There, however, we confined our study to the problem of finding the resultant; we shall now go further into the subject, but at this stage shall confine our study to the simpler kinds of beam, cantilevers and beams freely-supported and carrying only concentrated or "point" loads.

In Fig. 167, A, we have a member such as might be used as a beam, lying on a solid surface and supporting a load  $W$  at its centre. The reaction acts upwards on the underside over its length. This is not a beam because it is used in circumstances such that there can be no bending. (We are assuming that the member is rigid and the supporting

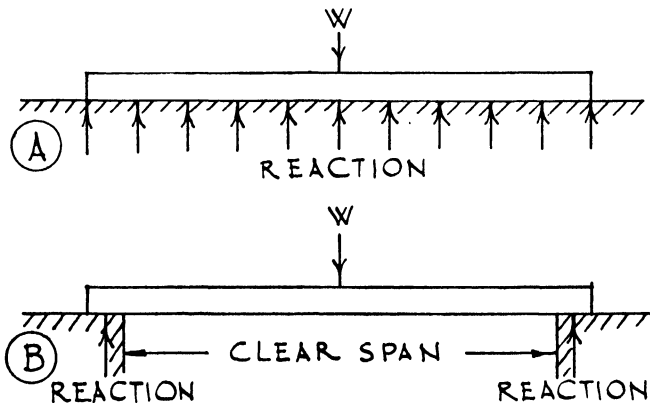


FIG. 167.—Load and Reactions on a Beam.

surface unyielding.) But if we place this member across two walls or other supports so that we have a clear span, then it becomes a beam and the reaction is now concentrated at the ends. (See Fig. 167, B.) Under these conditions the beam is subjected to the action of three forces, the load  $W$  acting downwards in the centre, and the two reactions acting upwards at the ends. As the beam is in a state of equilibrium the sum of the two reactions must therefore equal  $W$ , and it is fairly clear that in the present case each is equal to  $\frac{W}{2}$ .

But all cases are by no means so obvious, and we must become acquainted with the principle by which the amounts of the reactions are found. All cases, however complicated the conditions, then become easy if we apply the principle.

The principle we apply is the *principle of moments* defined on page 189. When a beam rests on supports it is the *effective span* which must be used for the purposes of calculation, and this is explained in Fig. 168, A. In some cases, for instance in a steel-framed building, a beam may be carried at its ends by web cleats riveted to steel pillars; the overall length, clear span and effective span are then identical. In any case we represent the beam diagrammatically as in Fig. 168, B, referring to the reactions as  $R_L$  (left reaction) and  $R_R$  (right reaction). This is important for clearness and also because the reaction may constitute a load in a further calculation for beam, pillar or wall, and we must be sure of taking the correct reaction for this purpose.

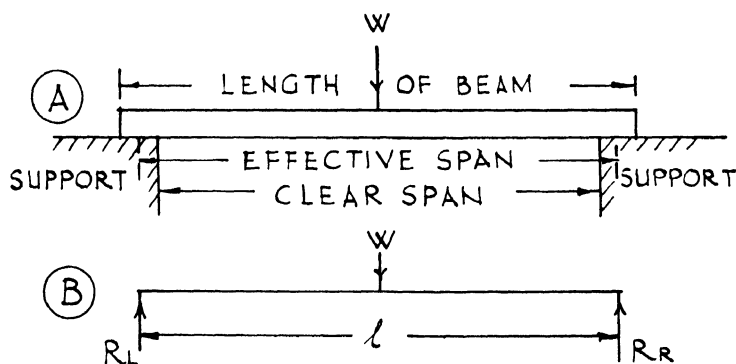


FIG. 168.—Effective Span of a Beam.

Applying the Principle of Moments to the beam, the sum of the moments of the three forces *about any point* is zero, in other words the sum of the clockwise moments will equal the sum of the anti-clockwise moments. Considering the beam shown in Fig. 169 let us take the point P as our moment-centre.

About P Clockwise moments =  $(4 \text{ tons} \times 25\text{-ft.}) = 100\text{-ft. tons.}$   
 Anti-clock. „ =  $(R_L \text{ tons} \times 10\text{-ft.}) + (R_R \times 40\text{-ft.})$   
 Therefore  $(R_L \times 10\text{-ft.}) + (R_R \times 40\text{-ft.}) = 100\text{-ft. tons.}$

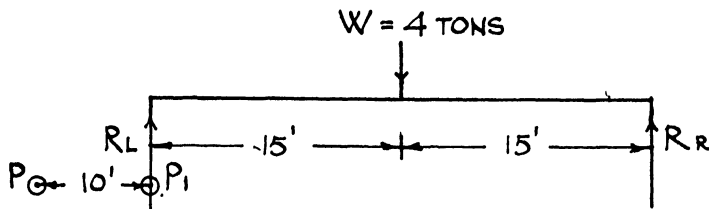


FIG. 169.—Choice of Moment-Centre for a Beam.

It is seen that here we have two unknown quantities in the equation. If we can arrange to have only one unknown the solution will be much more simple. Let us therefore take  $P_1$  as our moment centre.

About  $P_1$  Clockwise moment =  $(4 \text{ tons} \times 15\text{-ft.}) = 60\text{-ft. tons.}$

Anti-clock. „ =  $(R_L \times 0) + (R_R \times 30\text{-ft.})$

Now  $R_L \times 0 = 0$ , in other words  $R_L$  has no leverage about point  $P_1$  because  $P_1$  lies in the line of action of  $R_L$ .

Therefore  $(R_R \times 30\text{-ft.}) = 60\text{-ft. tons.}$

and  $R_R = \frac{60\text{-ft. tons}}{30\text{-ft.}} = \underline{2 \text{ tons.}}$

Therefore  $R_L = W - R_R = 4 - 2 = \underline{2 \text{ tons.}}$

We see from this example that if we consider moments about  $R_L$  we obtain the value of  $R_R$ . Similarly we could find  $R_L$  by considering moments about  $R_R$ , but having found one of the reactions we may find the other by subtraction from the total downward load.

Let us now check the example experimentally.

EXPERIMENT 118.—To find the reactions of a simply-supported beam.

Arrange a 36-in. rule as shown in Fig. 170 or if desired a 30-in. rod may be used with the spring balances at its extremities. Take the

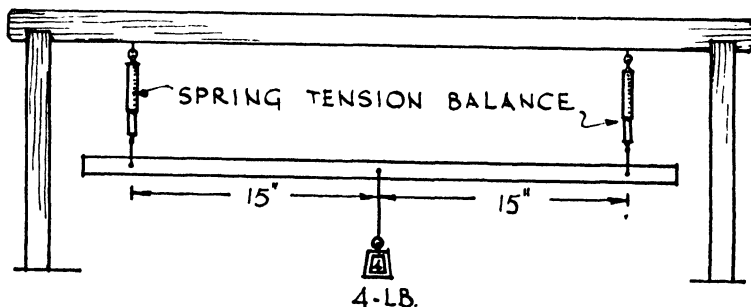


FIG. 170.—Reactions of a Beam Experimentally.

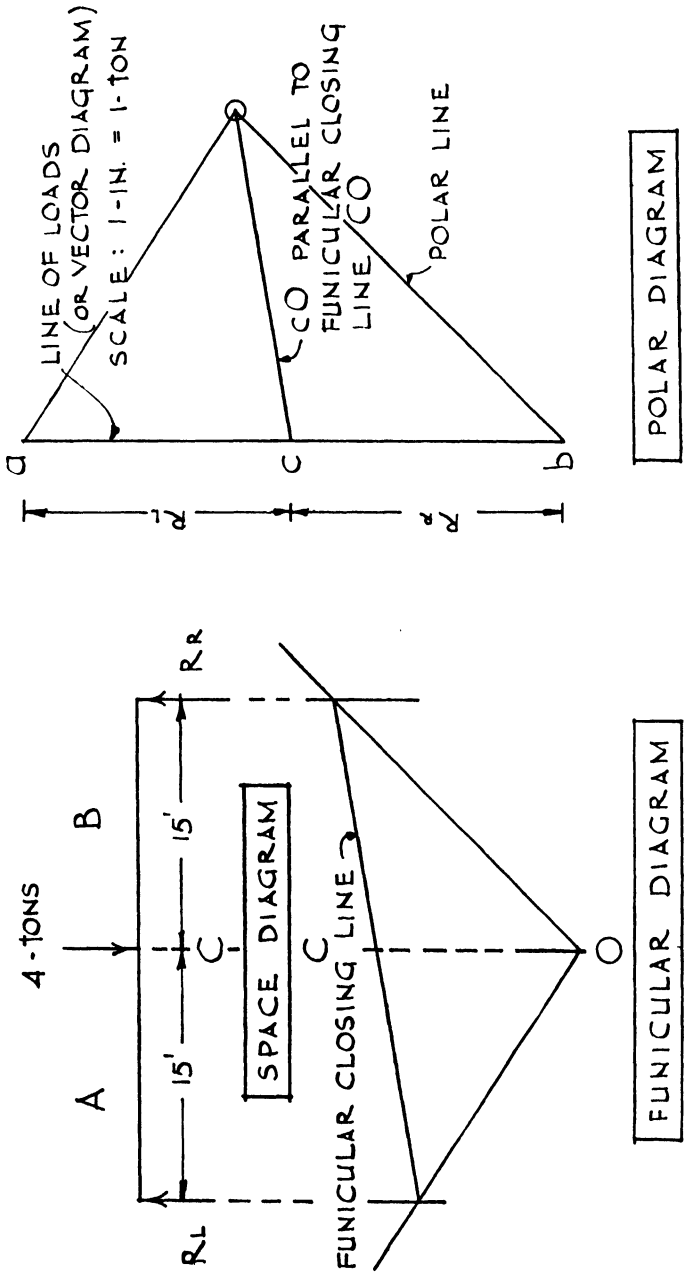


Fig. 171.—Reactions of a Beam Graphically.

balance readings due to the weight of the rod—in this case they were each  $\cdot 15$ -lb. Then suspend a 4-lb. weight from the centre and note the new readings,  $2\cdot 15$ -lb. each. Each reaction from the applied load is thus  $2\cdot 15 - \cdot 15 = 2$ -lb. so verifying the mathematical working.

(Our units are different as a matter of convenience only.)

In all the beam examples in the present volume we shall, for simplicity, ignore the weight of the beam itself. It is not considerable by comparison with the applied loads, but in more precise calculations it must of course be taken into account.

Now for the graphical treatment of this simple case.

Fig. 171 shows the construction. Draw first the space diagram to any scale and produce the lines of action of the forces. Next draw the vector diagram or line of loads;  $ab$  is the vector of force  $AB$  and as all the forces are vertical the vectors of the two reactions therefore lie on this line, and together will bring us back to point  $a$ . The problem is to find the position of point  $c$ .

Take any polar point  $O$ , draw polar lines  $aO$ ,  $bO$ , and parallel to these draw funicular lines  $AO$ ,  $BO$ . To complete the funicular diagram draw the funicular closing line  $CO$ , connecting the points at which the funicular lines  $AO$ ,  $BO$  cut  $R_L$  and  $R_R$  respectively. Now draw the corresponding polar line  $cO$ , so giving point  $c$  on the line of loads. Finally scale off  $bc$  and  $ca$ , so obtaining the magnitudes of the two reactions.

This simple case has been explained in detail so that future examples may be more or less self-explanatory from the diagrams.

In our next example, Fig. 172, the load is not central, but we follow the same procedure as before to find the reactions.

Taking moments about  $R_L$  :—

Clockwise moments = 4 tons  $\times$  22.5-ft. = 90-ft. tons.

Anti-clockwise „ =  $R_R \times 30$ -ft.

$R_R \times 30$ -ft. = 90-ft. tons.

and  $R_R = \frac{90\text{-ft. tons}}{30\text{-ft.}} = 3 \text{ tons.}$

Therefore  $R_L = 4 - 3 = 1 \text{ ton.}$

This may be checked experimentally as before. The graphical construction is also similar to the previous case.

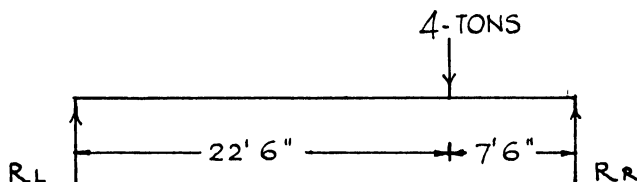


FIG. 172.—Reactions of Beam with Non-Central Load.



Let us now consider the case given in Fig. 173. We have the choice of two methods of procedure. We may find the amount of the reactions for each load in turn, subsequently adding to obtain the total reactions, or we may deal with all the loads in the same operation. The latter is the more straight forward way and is the one usually followed, but we will solve the problem by both methods so as to compare their merits.

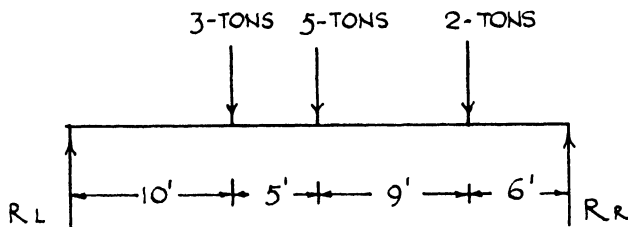


FIG. 173.—Reactions of Beam with several Point Loads.

*First Method.*—Dealing first with the 3-ton load.

Taking moments about  $R_L$  :—

$$\text{Clockwise moments} = 3 \text{ tons} \times 10\text{-ft.} = 30\text{-ft. tons.}$$

$$\text{Anti-clockwise „} = R_R \times 30\text{-ft.}$$

$$R_R \times 30\text{-ft.} = 30\text{-ft. tons}$$

$$\text{and } R_R = \frac{30\text{-ft. tons}}{30\text{-ft.}} = 1 \text{ ton.}$$

$$\text{Therefore } R_L = 3 - 1 = 2 \text{ tons.}$$

Dealing next with the 5-ton load.

As this load is central we know that half goes to each reaction.

$$\text{Therefore } R_R = 2.5 \text{ tons.}$$

$$\text{and } R_L = 2.5 \text{ tons.}$$

Dealing finally with the 2-ton load :—

Taking moments about  $R_L$  :—

$$\text{Clockwise moments} = 2 \text{ tons} \times 24\text{-ft.} = 48\text{-ft. tons.}$$

$$\text{Anti-clockwise „} = R_R \times 30\text{-ft.}$$

$$R_R \times 30\text{-ft.} = 48\text{-ft. tons.}$$

$$\text{and } R_R = \frac{48\text{-ft. tons}}{30\text{-ft.}} = 1.6 \text{ tons.}$$

$$\text{Therefore } R_L = 2 - 1.6 = .4 \text{ tons.}$$

We may now summarize :—

$$R_L = 2 + 2.5 + .4 = 4.9 \text{ tons.}$$

$$R_R = 1 + 2.5 + 1.6 = 5.1 \text{ tons.}$$

As a check we may compare the sum of the loads with the sum of the reactions :—

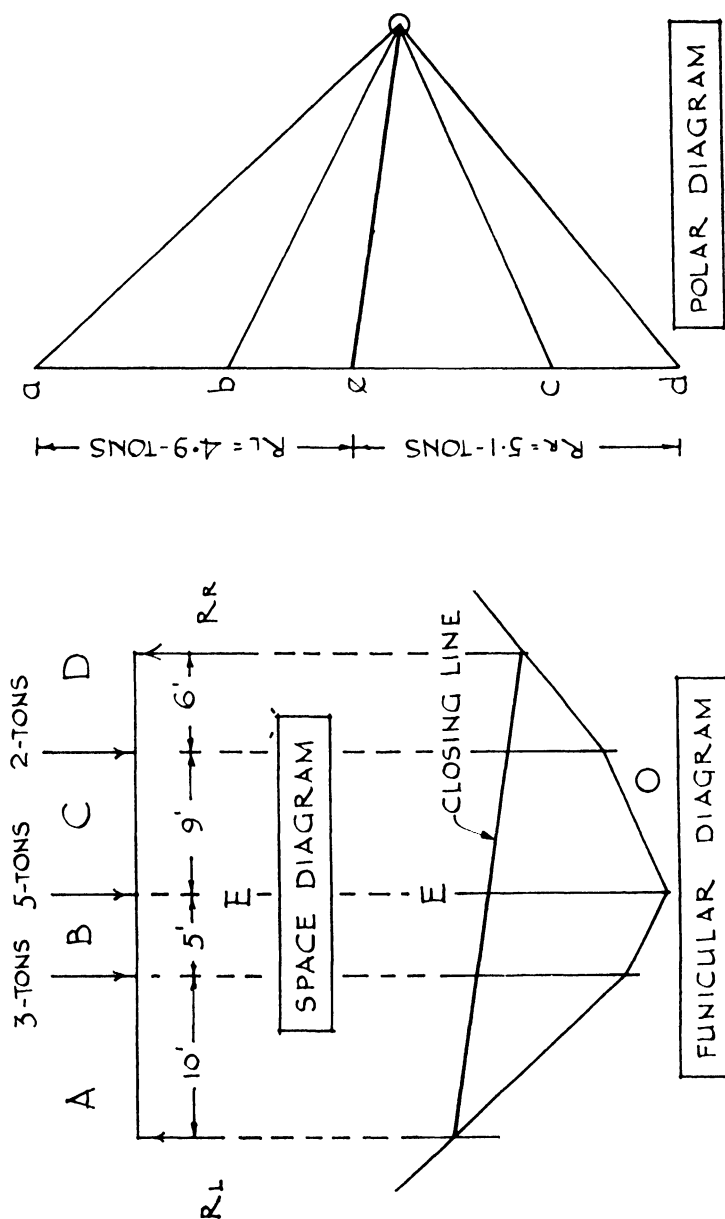


Fig. 174.—Graphical Solution of Reactions of Beam with Point Loading.

$$\text{Loads} \quad 3 + 5 + 2 = \underline{10 \text{ tons.}}$$

$$\text{Reactions} \quad 4.9 + 5.1 = \underline{10 \text{ tons.}}$$

*Second Method.*

Taking moments about  $R_L$  :—

$$\begin{aligned} \text{Clockwise moments} &= (3 \text{ tons} \times 10\text{-ft.}) + (5 \text{ tons} \times 15\text{-ft.}) \\ &\quad + (2 \text{ tons} \times 24\text{-ft.}) \\ &= 30 + 75 + 48 = 153\text{-ft. tons.} \end{aligned}$$

$$\text{Anti-clockwise} \quad ,, \quad = R_R \times 30\text{-ft.}$$

$$R_R \times 30\text{-ft.} = 153\text{-ft. tons.}$$

$$\text{and } R_R = \frac{153\text{-ft. tons}}{30\text{-ft.}} = \underline{5.1 \text{ tons.}}$$

$$\text{Therefore } R_L = (3+5+2) - 5.1 = \underline{4.9 \text{ tons.}}$$

This example should be checked experimentally as in Experiment 117. The graphical solution is identical in principle to the others but is complicated by the greater number of loads and a consequent greater liability to graphical error. It is shown in Fig. 174.

Our next example is that shown in Fig. 175. This differs from the previous case only in the fact that one of the reactions is some distance from the end of the beam. It may thus have an appearance unfamiliar to the student, but the solution follows the same lines as before.

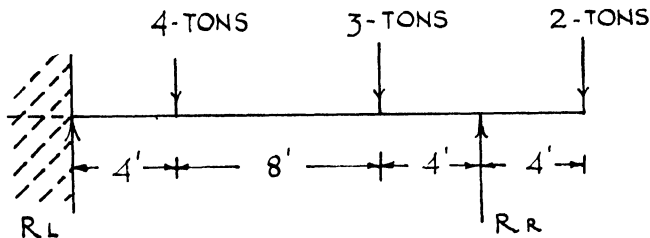


FIG. 175.—Beam overhanging 1 Support—Mathematical Treatment.

Taking moments about  $R_L$  :—

$$\begin{aligned} \text{Clockwise moments} &= (4 \text{ tons} \times 4\text{-ft.}) + (3 \text{ tons} \times 12\text{-ft.}) \\ &\quad + (2 \text{ tons} \times 20\text{-ft.}) \end{aligned}$$

$$\text{Anti-clockwise} \quad ,, \quad = R_R \times 16\text{-ft.}$$

$$R_R \times 16\text{-ft.} = 16 + 36 + 40 = 92\text{-ft. tons.}$$

$$\text{and } R_R = \frac{92\text{-ft. tons}}{16\text{-ft.}} = \underline{5.75 \text{ tons.}}$$

$$\text{Therefore } R_L = (4+3+2) - 5.75 = \underline{3.25 \text{ tons.}}$$

The experimental check would be arranged as follows :—

**EXPERIMENT 119.**—To find the reactions of a beam continuous over one of its supports.

Use a rod 20-in. long and arrange the weights and balances as in Fig. 176. Take the balance readings before applying the weights and call these initial readings zero in each case. The subsequent readings (from zero) should then verify the mathematical results.

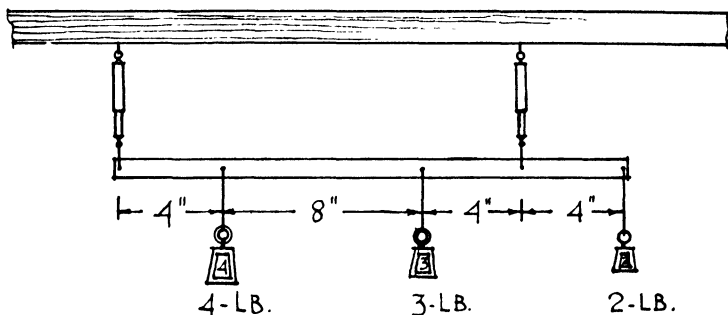


FIG. 176.—Beam overhanging 1 Support—Experimental Treatment.

Fig. 177 (see page 226) gives the graphical solution and this should be carefully studied as regards the extent of the funicular lines.

One further example (Fig. 178) is given in order to show a possible result of using this type of beam.

Taking moments about  $R_L$  :—

$$R_R \times 10\text{-ft.} = (4 \text{ tons} \times 6\text{-ft.}) + (3 \text{ tons} \times 16\text{-ft.})$$

$$= 24 + 48 = 72\text{-ft. tons.}$$

$$\text{and } R_R = \frac{72\text{-ft. tons}}{10\text{-ft.}} = \underline{7.2 \text{ tons.}}$$

$$R_L = (4 + 3) - 7.2 = \underline{-.2 \text{ tons.}}$$

It is seen that, for equilibrium, a downward force is necessary at  $R_L$ . It is thus important to find  $R_R$  first, as its direction is already known; had we taken moments about  $R_R$  we might have concluded that  $R_L$  was an upward reaction as usual.

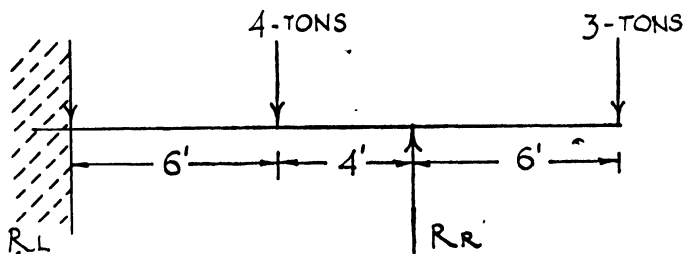


FIG. 178.—Overhanging Beam with Positive Reaction—Mathematically.

An experimental check will confirm our result.—

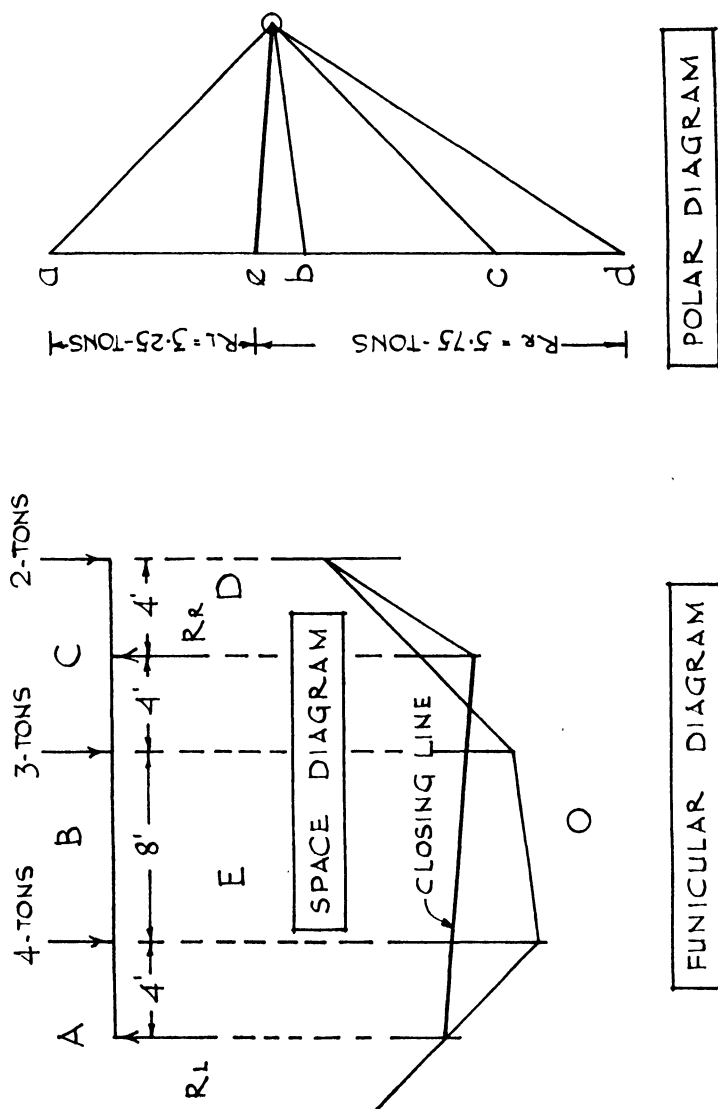


FIG. 177.—Beam overhanging 1 Support—Graphical Treatment.

## EXPERIMENT 120.

By the arrangement shown in Fig. 179 it is found that the balance corresponding to  $R_L$  shows no reading and that a further weight of 2-lb. must be suspended from this point to produce equilibrium.

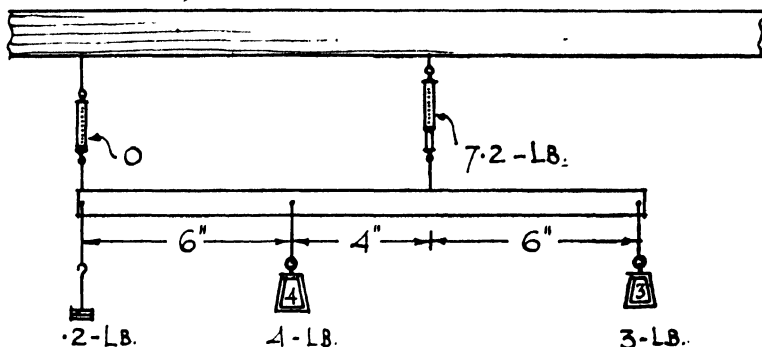


FIG. 179.—Overhanging Beam with Positive Reaction—Experimentally.

The graphical solution differs in appearance from the last example, as is seen from Fig. 180.

## 2. BENDING MOMENTS.

Beams are designed primarily to resist bending stresses, and as we have seen on page 191 these are produced by moments. Having found the amounts of the reactions for any beam we know all the forces acting on the beam and the next step is to discover the amount of moment induced by them in the various parts of the beam.

**CANTILEVER WITH POINT LOAD AT FREE END.**—The simplest case to illustrate this point is the simple cantilever shown in Fig. 181. As will be seen it is a beam with one support only. Simple cantilevers are rare in practice, except upon a small scale as brackets; instead, a cantilever is invariably a portion of a beam continued over a support, as in the last two examples, and is calculated accordingly. Referring to Fig. 181, A the effect of the load carried at the extremity is to produce a moment at all points along the beam. It is clearly greatest at the support as shown at B and is equal to:—load  $\times$  leverage or 2 tons  $\times$  6-ft. = 12-ft. tons. At point X, 3-ft. from the load its amount is still:—load  $\times$  leverage, now however 2 tons  $\times$  3-ft. = 6-ft. tons. Similarly at other points along the cantilever.

Fig. 181, D, shows how we may represent the moments diagrammatically. This is a *bending moment diagram*, and as the moment decreases uniformly from maximum at the support to zero at the free end, we need only calculate the amount of the *maximum* bending moment (B.M. max.)

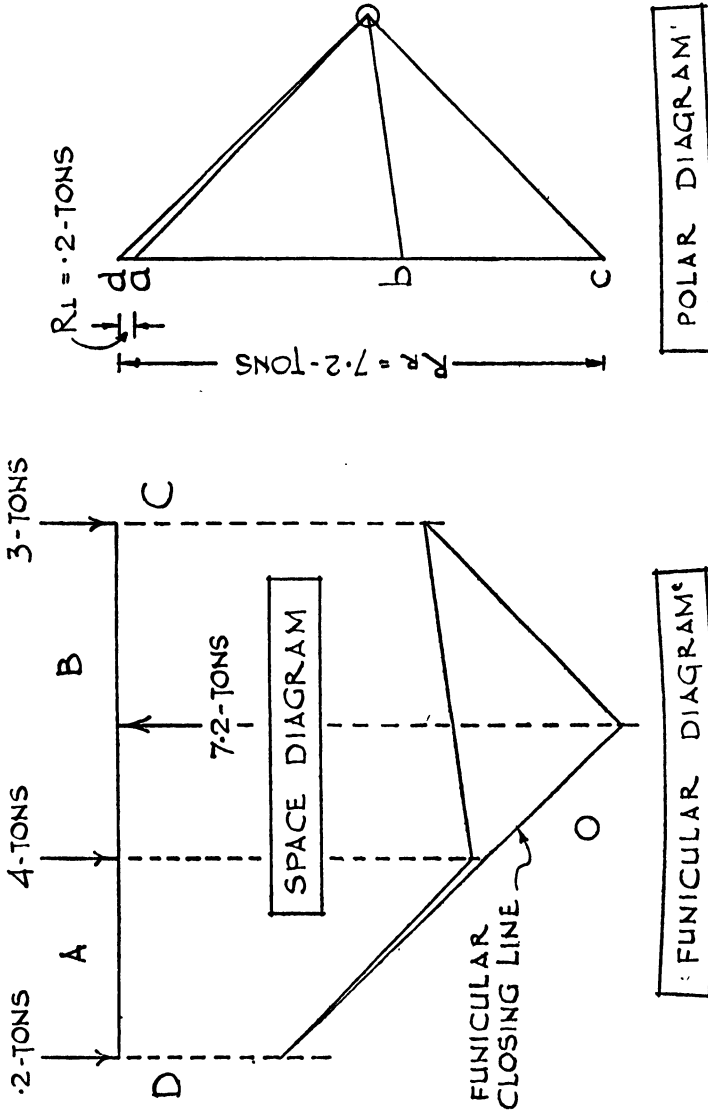


Fig. 180.—Overhanging Beam with Positive Reaction—Graphically.

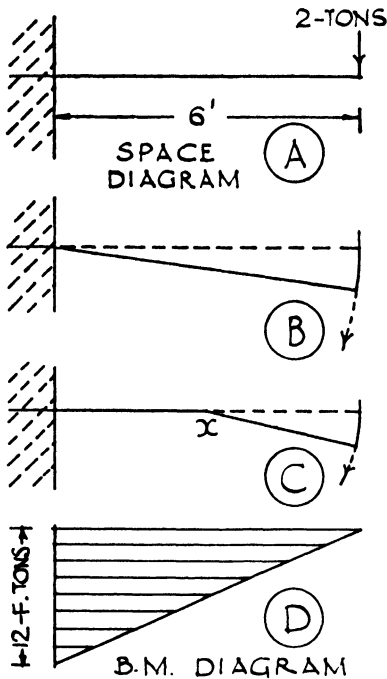


FIG. 181.—Bending Moments on a Cantilever.

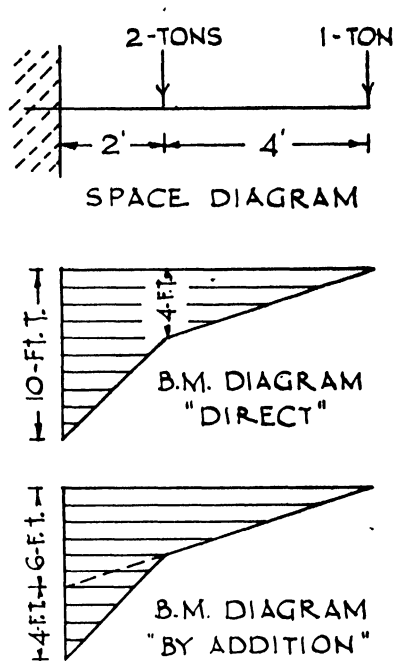


FIG. 182.—Bending Moments—Cantilever with Point Loads.

and set up the diagram. The amount of the bending moment at any other point along the cantilever is thus represented by the appropriate ordinate in the diagram.

The following rule applies to all cantilevers of this kind:—*The Bending Moment at any point along a cantilever is the sum of the moments, taken about that point, of all forces acting on the cantilever between that point and the free end.*

CANTILEVER WITH SEVERAL POINT LOADS.—If we have a simple cantilever supporting a number of loads as in Fig. 182 we may set up the diagram in one operation thus:—

$$\begin{aligned}\text{B.M. at support} &= (2 \text{ tons} \times 2\text{-ft.}) + (1 \text{ ton} \times 6\text{-ft.}) \\ &= 4 + 6 = \underline{10\text{-ft. tons.}}\end{aligned}$$

$$\begin{aligned}\text{B.M. at 2-ft. from support} &= 1 \text{ ton} \times 4\text{-ft.} \\ &= \underline{4\text{-ft. tons.}}\end{aligned}$$

$$\text{B.M. at free end} = 0$$

Or we may set up separate diagrams, afterwards combining or "adding" them as at C.

$$\begin{aligned}\text{B.M. at support for 2-ton load} &= 2 \text{ tons} \times 2\text{-ft.} \\ &= \underline{4\text{-ft. tons.}}\end{aligned}$$



$$\begin{aligned}\text{B.M. at support for 1-ton load} &= 1 \text{ ton} \times 6\text{-ft.} \\ &= \underline{6\text{-ft. tons.}}\end{aligned}$$

**SUPPORTED BEAM WITH CENTRAL POINT LOAD.**—The following rule applies to all beams freely supported at two points:—*The Bending Moment at any point along a loaded beam is the algebraic sum of the moments, taken about that point, of all forces acting on that portion of the beam on either side of the point.*

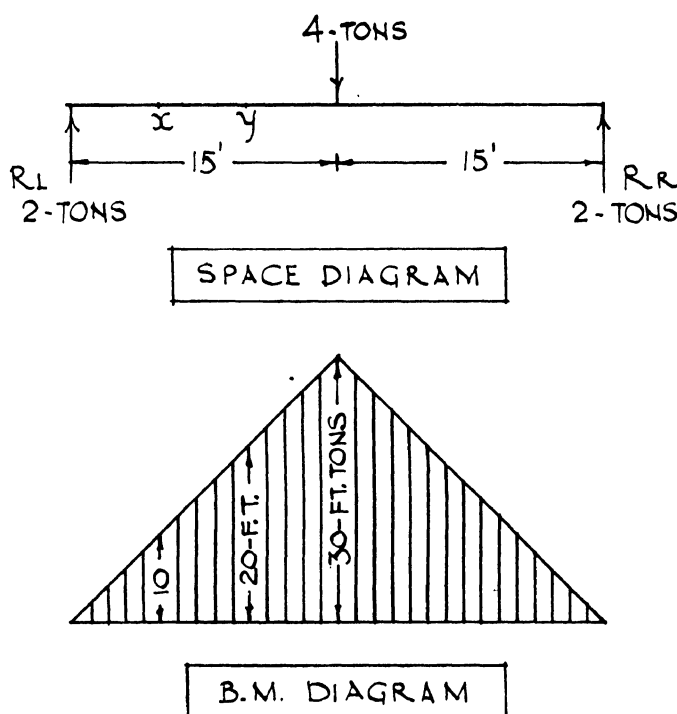


FIG. 183.—Bending Moments—Beam with Central Load.

Applying the rule to the present case, Fig. 183, we find some of the bending moments to be as follows:—

$$\begin{aligned}\text{B.M. at } R_L &= 2 \text{ tons} \times 0 &= \underline{0} \\ \text{or B.M. at } R_L &= (4 \text{ tons} \times 15\text{-ft.}) - (2 \text{ tons} \times 30\text{-ft.}) \\ &= 60 - 60 &= \underline{0} \\ \text{B.M. at } x, 5\text{-ft. from } R_L &= 2 \text{ tons} \times 5\text{-ft.} &= \underline{10\text{-ft. tons.}} \\ \text{or B.M. at } x &= (4 \text{ tons} \times 10\text{-ft.}) - (2 \text{ tons} \times 25\text{-ft.}) \\ &= 40 - 50 &= \underline{-10\text{-ft. tons.}}\end{aligned}$$

(Note that + and - refer simply to clockwise and anti-clockwise moments. "Positive" and "Negative" are used in this connection in an arbitrary way, merely to denote opposite directions).

$$\begin{aligned}
 \text{B.M. at } y, 10\text{-ft. from } R_L &= 2 \text{ tons} \times 10\text{-ft.} = \underline{20\text{-ft. tons.}} \\
 \text{or B.M. at } y &= (4 \text{ tons} \times 5\text{-ft.}) - (2 \text{ tons} \times 20\text{-ft.}) \\
 &= 20 - 40 = \underline{-20\text{-ft. tons.}} \\
 \text{B.M. at centre} &= 2 \text{ tons} \times 15\text{-ft.} = \underline{30\text{-ft. tons}} \\
 &\text{(whichever portion of the beam we consider).}
 \end{aligned}$$

Similarly with the other half of the beam. We can now set up the Bending Moment diagram, from which it will be seen that each half of the beam is like an inverted cantilever, and that we need only to calculate the B.M. at a point under the load and join by straight lines to the ends of the base line.

**POSITIVE AND NEGATIVE BENDING.**—Bending moments are termed "positive" and "negative" according to the direction of the bending. When the top of the beam assumes a concavity and the bottom a convexity, such as at A in Fig. 184, we term it positive bending. When the reverse is the case, as at B, we call it negative bending. This distinction is merely a matter of convenience because in some cases, *e.g.* at C, we get both positive and negative bending in the same beam. Certain portions of the bending moment diagram may sometimes cancel each other owing to the positive bending moment induced by one load being counteracted by negative bending induced by another. Because of this it is customary to hatch with parallel lines the extent of the bending moment diagram, vertical hatching for areas of positive B.M. and horizontal hatching for areas of negative B.M. It is also the custom to show positive areas *above* the base line and negative areas *below* it, although in a very occasional case it may be simpler to ignore this rule. Fig. 181, D, is an example of a negative B.M. diagram, whilst Fig. 183 shows positive moments.

**SUPPORTED BEAM WITH POINT LOAD NOT CENTRAL.**—Fig. 185 shows the beam whose reactions we calculated on page 221. To set up the B.M. diagram we calculate the bending moment at the load point (which we now know to be the point of maximum B.M.) :—

$$\begin{aligned}
 \text{B.M. at load} &= 1 \text{ ton} \times 22.5\text{-ft.} = \underline{22.5\text{-ft. tons.}} \\
 \text{or B.M. at load} &= 3 \text{ tons} \times 7.5\text{-ft.} = \underline{22.5\text{-ft. tons.}}
 \end{aligned}$$

Set this up to scale in order to produce the B.M. diagram as shown.

This B.M. diagram is "set up" from calculated data. We can also "draw" the B.M. diagram by graphical construction and this is shown

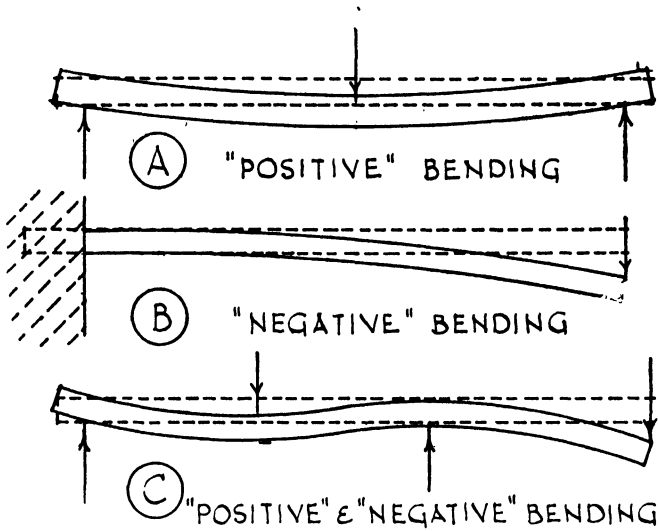


FIG. 184.—Positive and Negative Bending.

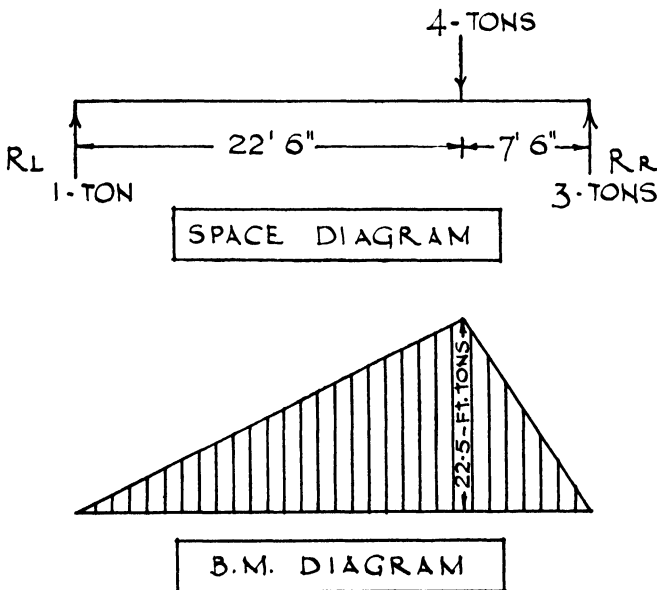


FIG. 185.—Bending Moments—Beam with Non-Central Load.

in Fig. 186. The procedure is to draw a polar and a funicular diagram as before, but in this case we need not find the amounts of the reactions. The funicular closing line is the base line of the B.M. diagram and the

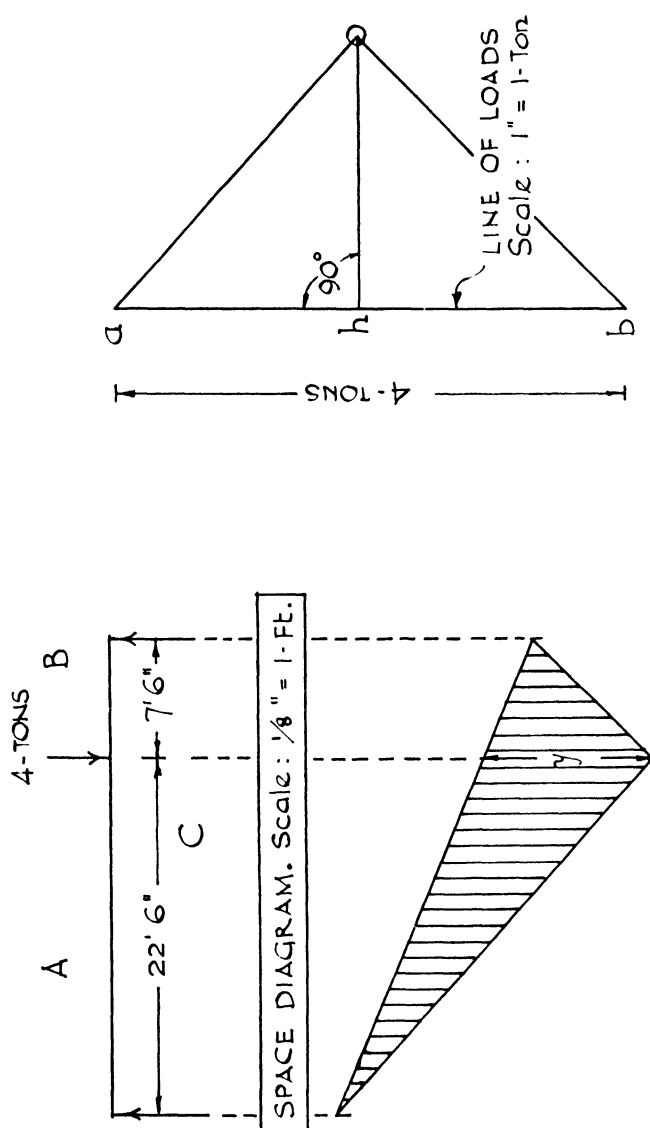


FIG. 186.—Bending Moments—Beam with Non-Central Load—Graphical Treatment.

ordinates represent to scale the bending moments. But the scale clearly depends upon the position of the polar point, since the further away this is from the line of loads the "shallower" the funicular diagram.

To find the scale, or rather to find the amount of B.M. say at  $y$ , we must scale off this ordinate (to the linear scale,  $\frac{1}{8}$ -in. = 1-ft.) and multiply it by the *polar distance*  $oh$  (measured to the force scale, 1-in. = 1 ton). This gives us  $10.7\text{-ft.} \times 2.1 \text{ tons} = \underline{22.5\text{-ft. tons.}}$  The B.M. at any other point is found similarly, the appropriate ordinate  $\times oh$ .

**SUPPORTED BEAM WITH SEVERAL POINT LOADS.**—We will take the case for which we found the reactions on page 222. Referring to Fig. 187 it will be seen that we have placed the polar point to the *left* of the line of loads merely to show that the only effect is to reverse the funicular diagram. In addition we have deliberately placed it at a definite distance (2-in.) in order to eliminate one source of graphical error. Such error need now only arise from measuring the length of the ordinate.

Let us find the amount of B.M. at  $y$ , 12-ft. from  $R_L$  :—

$$\text{Ordinate } y \text{ (to linear scale)} = 13.2\text{-ft.}$$

$$\text{Polar distance } Oh = 2\text{-in. representing } 4 \text{ tons.}$$

$$\text{Therefore B.M. at } y = 13.2\text{-ft.} \times 4 \text{ tons} = \underline{52.8\text{-ft. tons.}}$$

The mathematical treatment is as follows :—

$$\text{B.M. at 10-ft. from } R_L = (4.9 \text{ tons} \times 10\text{-ft.}) = \underline{49\text{-ft. tons.}}$$

$$\begin{aligned} \text{B.M. at 15-ft. from } R_L &= (4.9 \text{ tons} \times 15\text{-ft.}) - (3 \text{ tons} \times 5\text{-ft.}) \\ &= 73.5 - 15 = \underline{58.5\text{-ft. tons.}} \end{aligned}$$

$$\text{B.M. at 24-ft. from } R_L = (5.1 \text{ tons} \times 6\text{-ft.}) = \underline{30.6\text{-ft. tons.}}$$

The "set up" B.M. diagram is given in Fig. 188, from which the B.M. at  $y$  is 52.8-ft. tons.

$$\begin{aligned} \text{Mathematically the B.M. at } y &= (4.9 \text{ tons} \times 12\text{-ft.}) - (3 \text{ tons} \times 2\text{-ft.}) \\ &= 58.8 - 6 = \underline{52.8\text{-ft. tons.}} \end{aligned}$$

**BEAM OVERHANGING ONE SUPPORT.**—Our next example is the one given in Figs. 175 and 189 and we already know the reactions to be 3.25 tons and 5.75 tons respectively.

$$\text{B.M. at 4-ft. from } R_L = 3.25 \text{ tons} \times 4\text{-ft.} = \underline{13\text{-ft. tons.}}$$

$$\begin{aligned} \text{B.M. at 12-ft. from } R_L &= (3.25 \text{ tons} \times 12\text{-ft.}) - (4 \text{ tons} \times 8\text{-ft.}) \\ &= 39 - 32 = \underline{7\text{-ft. tons.}} \end{aligned}$$

$$\text{B.M. at } R_R = 2 \text{ tons} \times 4\text{-ft.} = \underline{8\text{-ft. tons.}}$$

The graphical solution is given in Fig. 190.

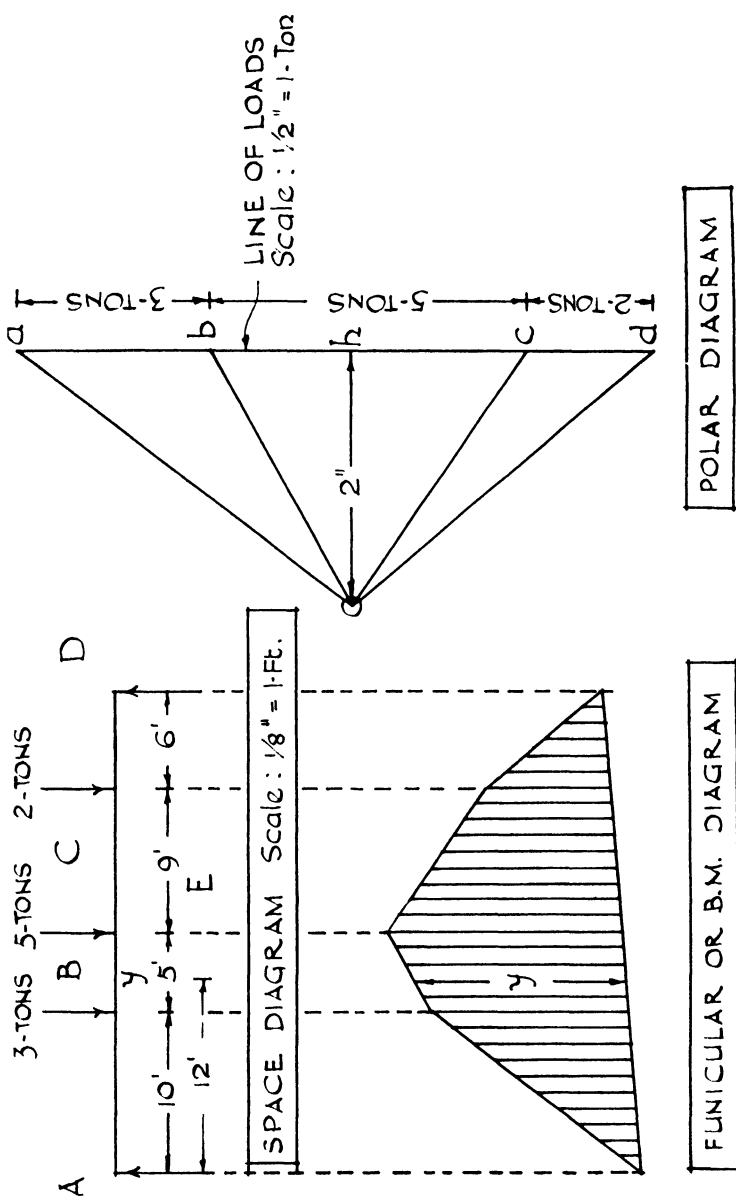


Fig. 187.—Beam with several Point Loads—Bending Moments Graphically.

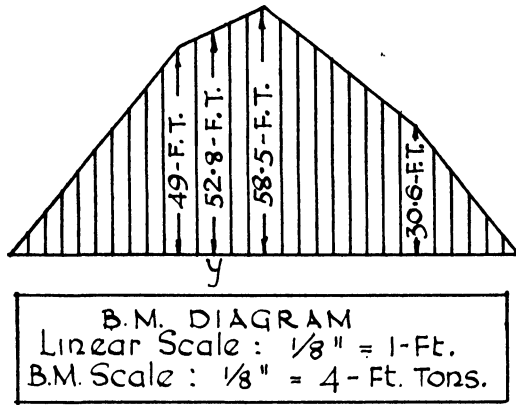


FIG: 188.—Bending Moment Diagram set up from Calculated Data

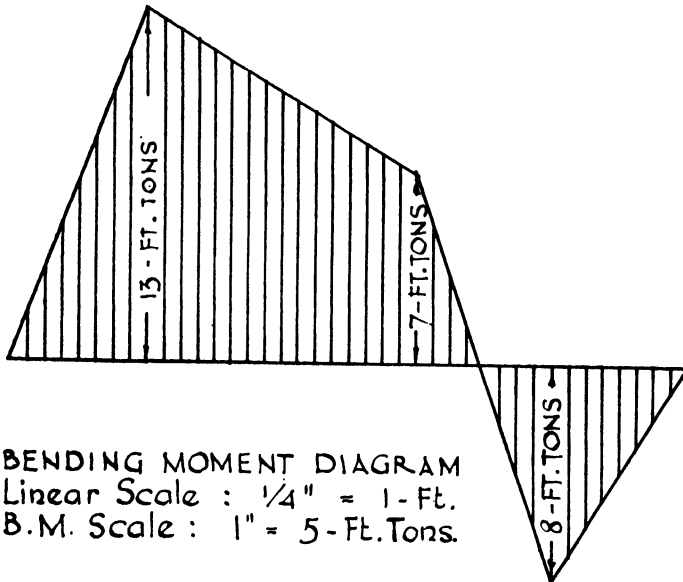
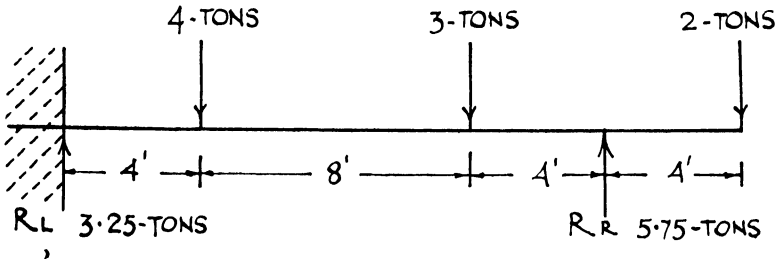


FIG. 189.—Beam overhanging 1 Support—B.M. Diagram "set up."

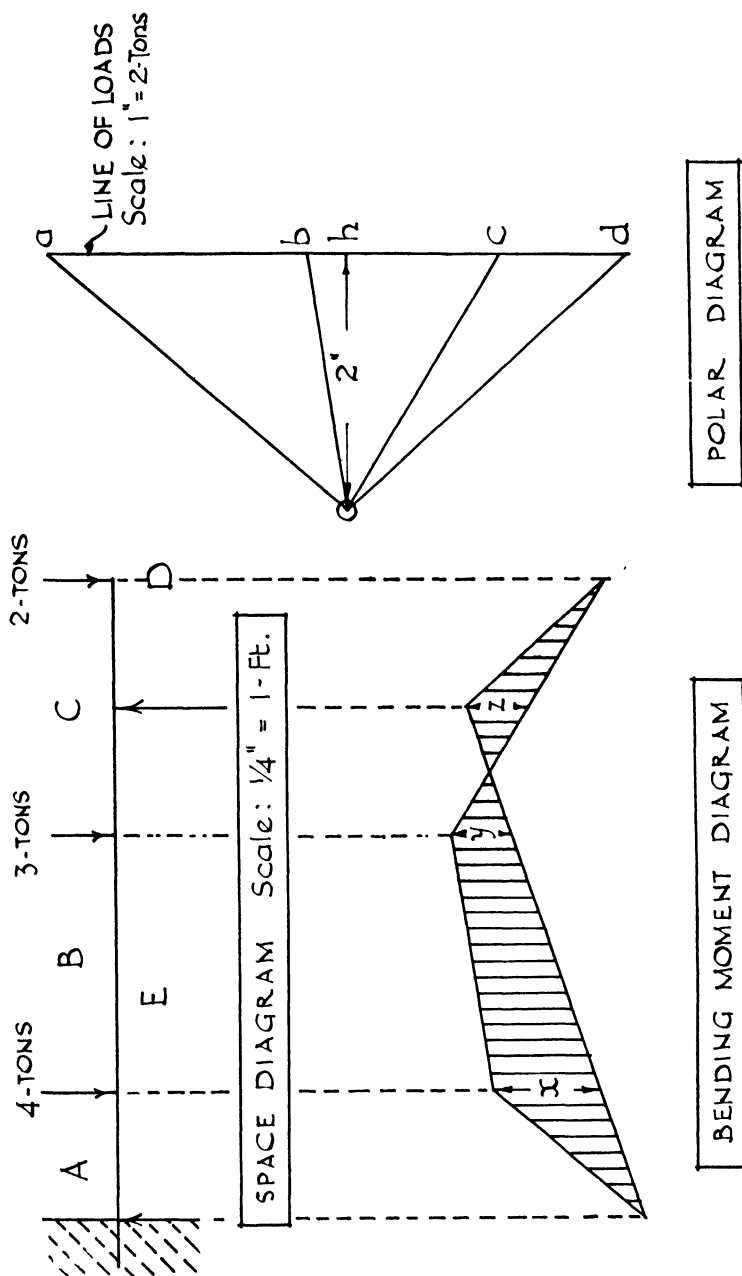


FIG. 190.—Beam overhanging 1 Support—B.M. Diagram Graphically.



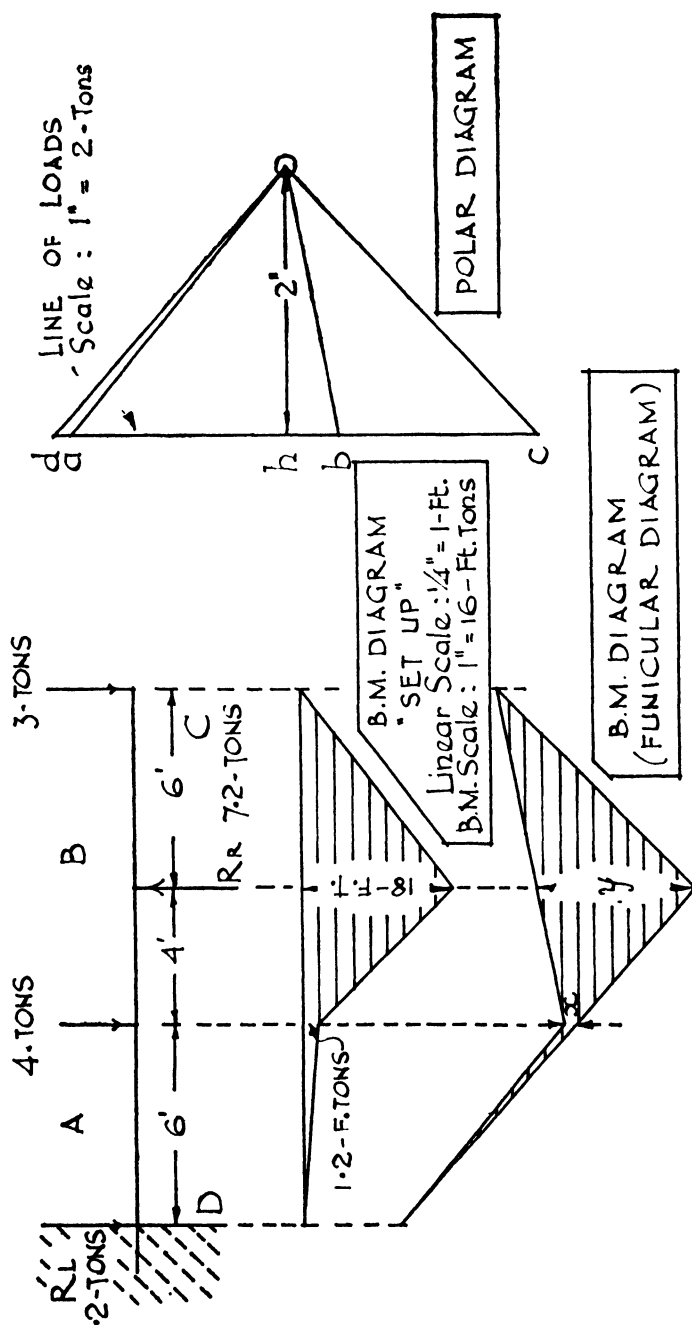


FIG. 191.—Overhanging Beam with Positive Reaction—B.M. Diagram "set up" and drawn Graphically.

From this B.M. at  $x = 3.25\text{-ft.} \times 0h$  (4 tons) = 13-ft. tons.

B.M. at  $y = 1.75\text{-ft.} \times 0h$  = 7-ft. tons.

B.M. at  $z = 2\text{-ft.} \times 0h$  = 8-ft. tons.

BEAM WITH WHOLLY NEGATIVE MOMENTS.—Our final case is that given in Figs. 178 and 191.

B.M. at 6-ft. from  $R_L$  =  $2 \text{ tons} \times 6\text{-ft.}$  = 12-ft. tons.

B.M. at  $R_R$  =  $(3 \text{ tons} \times 6\text{-ft.})$  = 18-ft. tons.

From the graphical construction :—

B.M. at  $x$  =  $3\text{-ft.} \times 4 \text{ tons}$  = 12-ft. tons.

B.M. at  $y$  =  $4.5\text{-ft.} \times 4 \text{ tons}$  = 18-ft. tons.

BENDING MOMENTS EXPERIMENTALLY.—As the amount of a moment is the product of two units, those of force and distance, there can be no means of measuring moments directly. Nevertheless we can obtain experimental verification of bending moments for simple cases with the apparatus shown in Fig. 192.

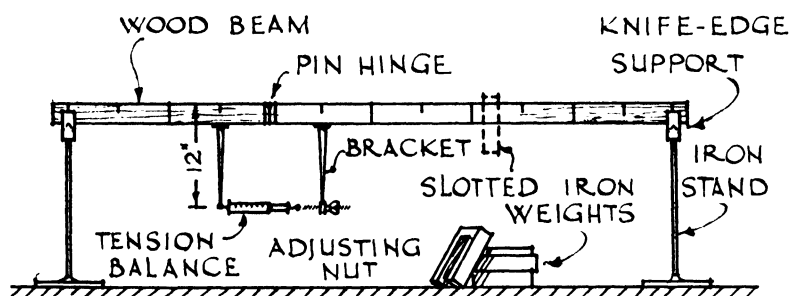


FIG. 192.—Experimental Treatment of Bending Moments.

It comprises a wooden beam about 1-in. wide and 3-in. deep, a little over 6-ft. long. At a point just over 2-ft. from one end the beam is separated into two lengths by a pin hinge, but is maintained in a horizontal position by the pull of a spring tension balance held at a perpendicular distance of 1-ft. from the centre of the pin. The initial reading on this balance is taken as zero. When the beam is loaded the bending moment at this point causes it to deflect and the force in lb. recorded by the balance (minus zero reading) acting with a leverage of 1-ft. is identical numerically with the bending moment in ft. lb.

Let us make use of the apparatus to check our calculations for B.M. in a few simple cases.

## EXPERIMENT 121.

Arrange the beam as in Fig. 193, and adjust the balance until the beam is horizontal. Now take the initial balance reading as zero. It is found to be 5-lb. Now place 6-lb. in weights immediately over the hinge and take the new balance reading, which is found to be 13-lb. This minus our zero gives us 8-lb., corresponding to a B.M. of 8-ft.-lb. Let us check this mathematically. Referring to Fig. 193,

$$R_L = \frac{6\text{-lb.} \times 4\text{-ft.}}{6\text{-ft.}} = 4\text{-lb.}$$

$$\text{and B.M. at the load} = 4\text{-lb.} \times 2\text{-ft.} = \underline{8\text{-ft.-lb.}}$$

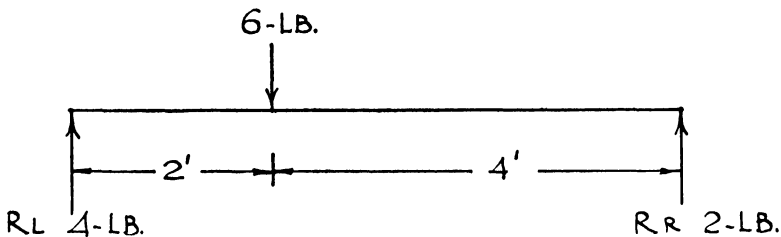


FIG. 193.—Beam with Non-Central Load—Experimental Solution of Bending Moments.

## EXPERIMENT 122.

Arrange the span of 5-ft. by moving the right-hand support inwards for 1-ft. as in Fig. 194. Find the new zero by adjusting the balance. Place a 4-lb. weight at midspan and deduct zero from the new reading. This is found to be  $8.25 - 4.25 = 4$ -lb. corresponding to a B.M. of 4-ft.-lb.

$$\begin{aligned} \text{Mathematically the B.M. at } x &= R_L \times 2\text{-ft.} \\ &= 2\text{-lb.} \times 2\text{-ft.} = \underline{4\text{-ft.-lb.}} \end{aligned}$$

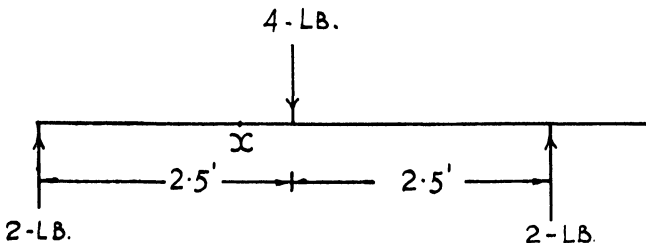


FIG. 194.—Beam with Central Load—Experimental Solution of Bending Moments.

## EXPERIMENT 123.

Reverse the apparatus so that it acts as a cantilever as in Fig. 195. Repeat the process of finding zero, applying the load, etc., and the reading is found to be  $5.75 - 1.75 = 4$ -lb. corresponding to a B.M. of 4-ft.-lb.

Mathematically the B.M. at the support = load  $\times$  leverage  
 $= 2$ -lb.  $\times$  2-ft. = 4-ft.-lb.

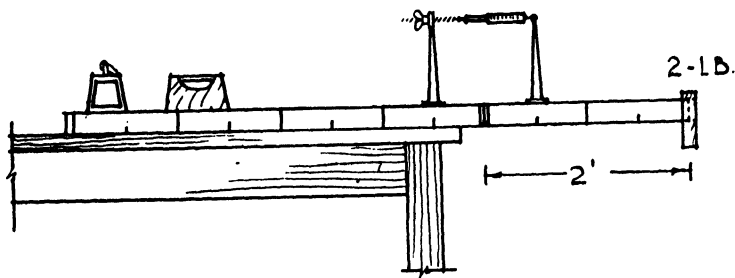


FIG. 195.—B.M. on Cantilever—Experimental Solution.

### 3. SHEARING STRESSES IN BEAMS.

A beam, being acted upon by a number of parallel forces, has to withstand shearing stresses in addition to bending stresses. In the vast majority of timber and steel beams, their strength to resist bending is the criterion; if they are strong enough in bending they are also strong enough in shear. But cases do occur, usually short beams carrying heavy loads, in which failure would take place by shearing rather than by bending. In reinforced concrete and large built-up steel beams the shearing stresses must be investigated and allowed for, whilst in footings of any magnitude the nature of the construction is such that shear must be taken into account.

We have seen how shear stresses are caused by the tendency of adjacent planes of the material to slide under the action of opposite forces acting at some distance from each other. This tendency may first be demonstrated simply by considering a timber beam to be composed of a number of blocks glued together vertically. Such a beam is shown at A in Fig. 196, whilst at B we see the result of the application of a load. The resistance of the glue has been overcome and the middle block has slid vertically past the adjacent ones. If the beam were solid the *tendency* to slide in this way would be present.

Fig. 197 shows a beam made up of boards glued together horizontally. At B we see that the effect of loading would be to cause the boards to slide horizontally over each other. This tendency is also present in the solid beam.

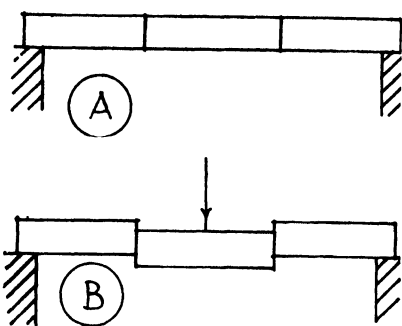


FIG. 196.—Showing Vertical Shear in a Beam.

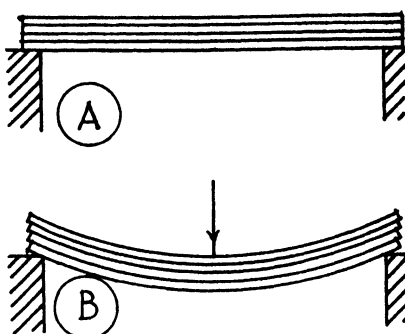


FIG. 197.—Showing Horizontal Shear in a Beam.

Fig. 198 illustrates a beam composed of blocks glued together, which shows that diagonal tension can occur, at right-angles to the direction of the joints shown.

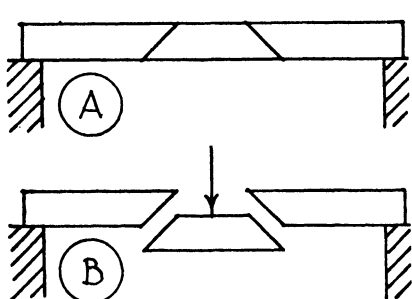


FIG. 198.—Showing Diagonal Tension in a Beam.

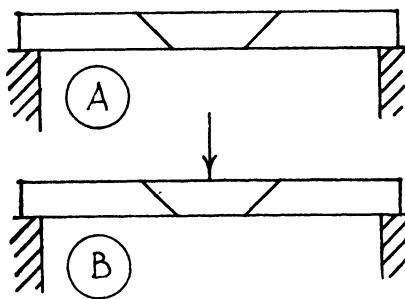


FIG. 199.—Showing Diagonal Compression in a Beam.

Finally, in Fig. 199, we see that compressive stresses can also occur in diagonal planes at right-angles to the tension.

All these tendencies are quite distinct from those caused directly by bending, and we will shortly consider how they arise and what relationship they bear to each other.

Let us now see how vertical and horizontal shear are brought about. Fig. 200 illustrates a piece of apparatus designed for this purpose, which we shall use in the two succeeding experiments.

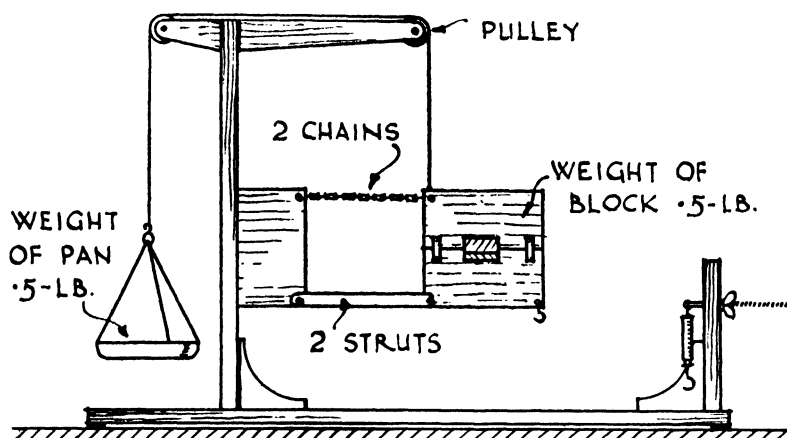


FIG. 200.—Apparatus for showing Vertical Shear in Cantilever.

EXPERIMENT 124.—To demonstrate vertical shear in a cantilever.

The apparatus represents a cantilever having a portion removed, the outer block being held in position by two chains across the top, two struts across the bottom, and a string passing over pulleys and terminating in a pan designed for holding weights. The weight of the outer portion of cantilever is .5-lb. and that of the pan .5-lb. The cantilever is now in equilibrium just as though it were solid throughout.

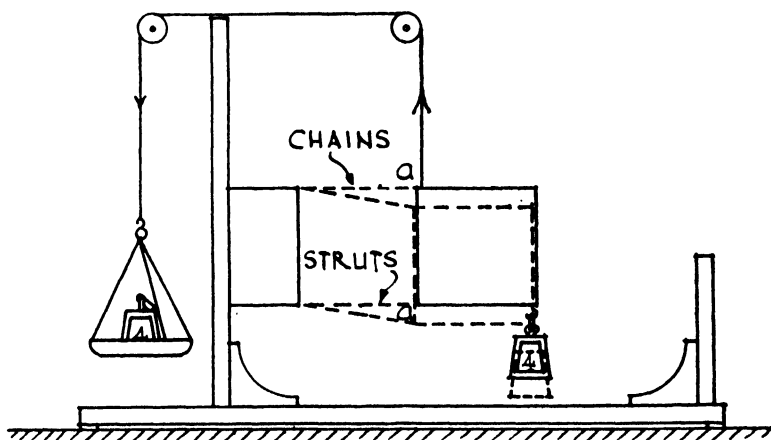


FIG. 201.—Vertical Shear in Cantilever—Experimentally.

Now suspend a weight of, say, 4-lb. from the hook at the extremity of the cantilever. The cantilever will deflect as shown by the dotted lines (Fig. 201) until equilibrium is restored by placing 4-lb. in weights in the pan.

From this experiment we see that the effect of applying a load to the free end of the cantilever is to produce a vertical shearing force along the plane *a-a*, also acting downwards since an upward force of equal amount is necessary to maintain equilibrium.

**EXPERIMENT 125.**—To show horizontal shear in a cantilever.

Keeping the cantilever in a state of equilibrium by leaving the weights in position, remove the folding wedges which are fitted into a slot on a horizontal plane midway in the depth of the cantilever. The two halves of the end block immediately slide apart, thus showing the existence of a horizontal shearing force along this plane.

In a subsequent volume we shall show that the amount of this shearing force varies in planes at different depths in the beam, being maximum at this particular plane.

**RULES FOR FINDING VERTICAL SHEAR.**—The direct cause of shear in a beam is the fact that opposite forces (loads and reactions) are acting at some distance from each other. As these are normally vertical forces vertical shear is produced.

*The vertical shear at any section of a cantilever is the algebraic sum of the forces acting on the portion of the cantilever between the given section and the free end.*

*The vertical shear at any section of a beam supported at the ends is the algebraic sum of the forces acting on the portion of the beam on either side of the given section.*

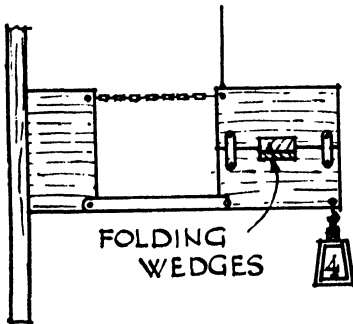


FIG. 202.—Horizontal Shear in Cantilever—Experimentally.

These opposite vertical forces act as couples (see page 193) and, as the beam is in equilibrium, induce horizontal couples equal in magnitude, these latter constituting the horizontal shear. This is shown in Fig. 203, where AB, CD represent the vertical couple and CB, AD the resulting horizontal couple. If we now consider the moment of AB about point C, and that of CB about point A we have :—

$$(f \times AB) \times BC = (f_1 \times BC) \times AB$$

$$\text{Therefore } f = f_1$$

or vertical shear = horizontal shear.

Again referring to Fig. 203, the equilibrant of AB and CB is BD, and that of AD and CD is DB. This is the diagonal tension mentioned earlier and it may be shown to be equal in magnitude to the vertical or horizontal shear.

Thus, assuming  $f$  and  $f_1$  to be unity,

Then Ten. =  $\sqrt{2} \times f$  and this is distributed over BD (which is equal to  $\sqrt{2}$ )

$$\text{Therefore Ten.} = \frac{\sqrt{2} \times f}{\sqrt{2}} = f.$$

Similarly the equilibrant of AB and AD is CA, and that of CB and CD is AC. This is diagonal compression acting at right-angles to the diagonal tension, and is similarly equal to  $f$ .

**EFFECT OF DIAGONAL TENSION AND COMPRESSION.**—If a *short* concrete beam be tested to destruction it will fail by cracking along diagonal planes as indicated in Fig. 204. Hence the need for reinforcing rods across the direction of these tension cracks. In Fig. 205 is shown part elevation and cross-section of a reinforced concrete beam. The main tensile reinforcement runs longitudinally near the lower edge of the section, but towards the supports the bending moment is reduced, necessitating fewer rods.

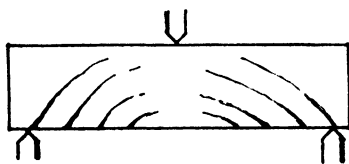


FIG. 204.—Effect of Diagonal Tension in Concrete Beam.

But as shear is usually greatest at the supports, some of these rods are bent up along the planes of diagonal tension, or alternatively separate tension rods introduced for this purpose. The diagonal compression acting in planes at right-angles requires no special provision as the concrete itself is well able to resist this.

If a *short* steel beam having a deep, thin web be tested to destruction it fails by buckling of the web after the manner shown in Fig. 206. In Fig. 207 is shown a deep steel beam such as a plate girder, usually built to carry heavy loads. If we imagine a diagonal strip of web, AB, it is easy to see that it would buckle readily under the compression as its length is considerable in relation to its thickness (usually  $\frac{3}{8}$ -in. or  $\frac{1}{2}$ -in.). In order to prevent the tendency to buckle, steel angle stiffeners are rivetted to both sides of the web, and these have the effect of reducing the

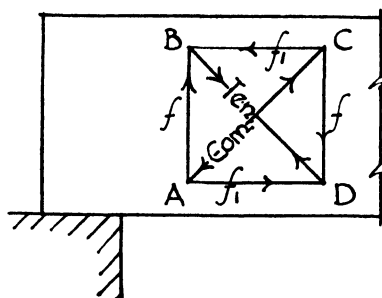


FIG. 203.—Diagonal Tension and Compression induced by Vertical and Horizontal Shear.



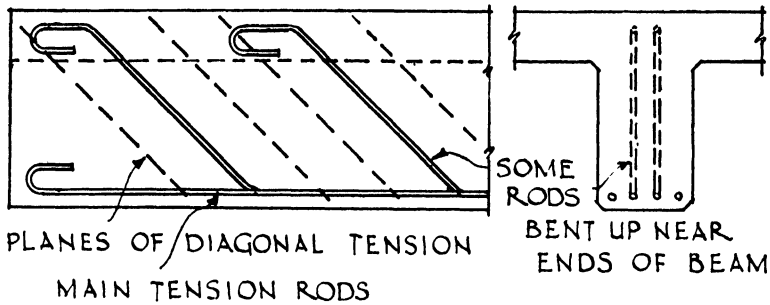


FIG. 205.—Precaution against Diagonal Tension.

effective length of the strip AB. From this will be clear the reason for the rule that such stiffeners must be spaced at distances apart less than the depth of the web. The thin web would of course be able to withstand

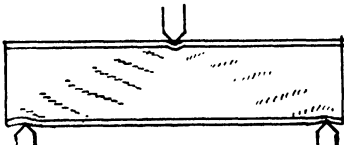


FIG. 206.—Effect of Diagonal Compression in Steel Beam.

the diagonal tension no matter what its depth. It is rarely that ordinary rolled steel section beams require stiffeners, except when used in foundations where loads may be exceptionally heavy.

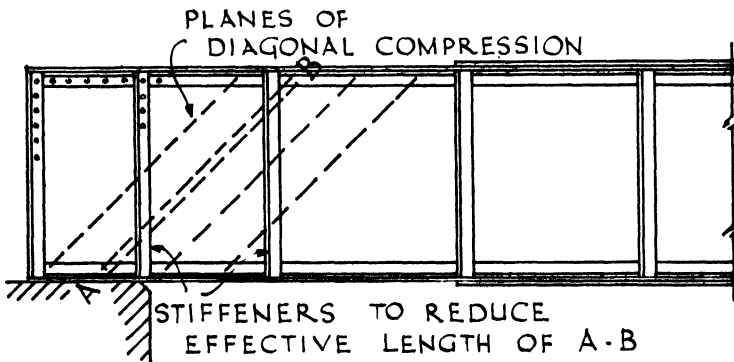


FIG. 207.—Precaution against Diagonal Compression.

Timber beams failing by shear always split longitudinally because this is the direction of the grain, and thus that of the weakest planes. They thus fail by horizontal shear.

**Shear Diagrams.**—Applying the rules to find the amount of vertical shear (page 244) we can construct a diagram showing the shear at all points along any beam or cantilever. We will take the same cases for which we constructed bending moment diagrams.

**CANTILEVER WITH POINT LOAD.**—The total force between any section and the free end is 2 tons, and the vertical shear is thus constant at all points along the cantilever. Fig. 208 shows the shear diagram.

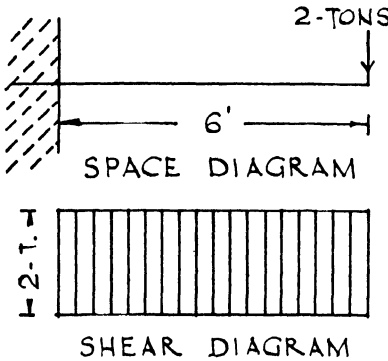


FIG. 208.—Vertical Shear Diagram—Cantilever with Point Load.

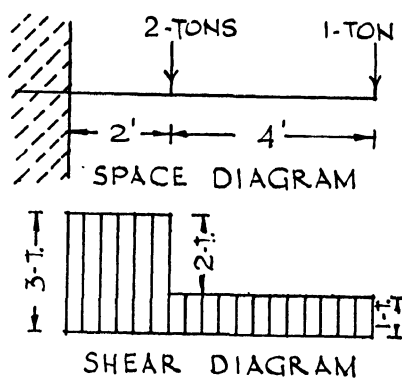


FIG. 209.—Shear Diagram—Cantilever with several Point Loads.

**CANTILEVER WITH SEVERAL POINT LOADS.**—Applying the rule, we have a shear force of 3 tons at all points between the support and the 2 tons load, and 1 ton for the remainder of the length. The diagram is thus as in Fig. 209.

**SUPPORTED BEAM WITH CENTRAL POINT LOAD.**—At all points along the beam the shear is 2 tons, but at midspan it “changes sign.” The reason for this will be clear if we consider the vertical shear diagram to be merely a graphical representation of the upward and downward forces. Thus, commencing at the extreme left of the base line we have  $R_L$  acting upwards. We therefore draw from this point a vertical line representing  $R_L$  to a convenient scale. To the right of  $R_L$  (in the space diagram) there are no other forces until we reach midspan. We therefore proceed horizontally (in the shear diagram) until we reach this point. At midspan we have the vertical load of 4 tons acting downwards. We therefore drop a vertical line representing 4 tons to scale, which brings us a distance representing 2 tons below the base line. To the right of the load (in the space diagram) there is no other load until we reach  $R_R$ . So we proceed horizontally again until we reach a point corresponding to  $R_R$  when we draw the vertical line upwards representing  $R_R$ , which brings us up exactly to the base line again.

The procedure has been explained in detail because if followed carefully any shear diagram may be set up without difficulty, no matter how complicated the loading, etc.

Referring to Fig. 210 it should be noted that at midspan the vertical shear is not 4 tons. Each ordinate of the shear diagram represents

scale the vertical shear at a point, and these points are an infinitely small distance apart. Fig. 211 may make for clearness; here we have exaggerated the distance between two adjacent points at midspan and this shows that the central line AB in Fig. 210 is not one ordinate of shear at this point but two ordinates an infinitely small distance from each other, the shear between them being zero.

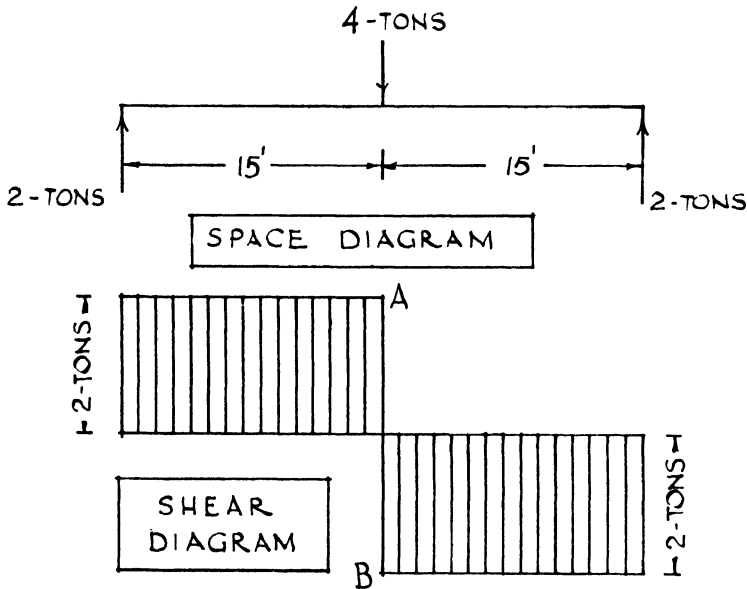


FIG. 210.—Shear Diagram—Beam with Central Load.

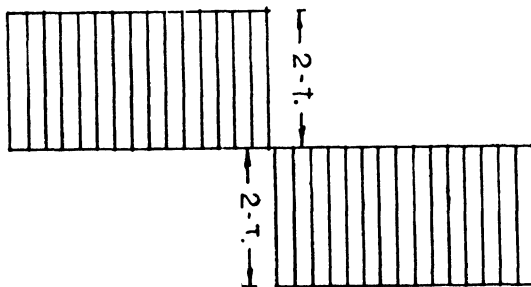


FIG. 211.—"Change of Sign" in Shear Diagram.

Fig. 212 shows the graphical construction for this case. The line of loads is of course the vector diagram of AB, BC, CA, and the points *a*, *b*, *c* are projected horizontally to intersect the lines of action of the forces, so giving the diagram.

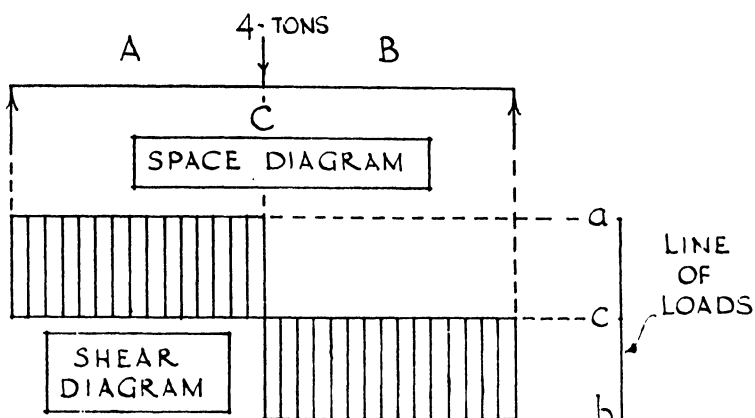


FIG. 212.—Shear Diagram—Graphical Treatment.

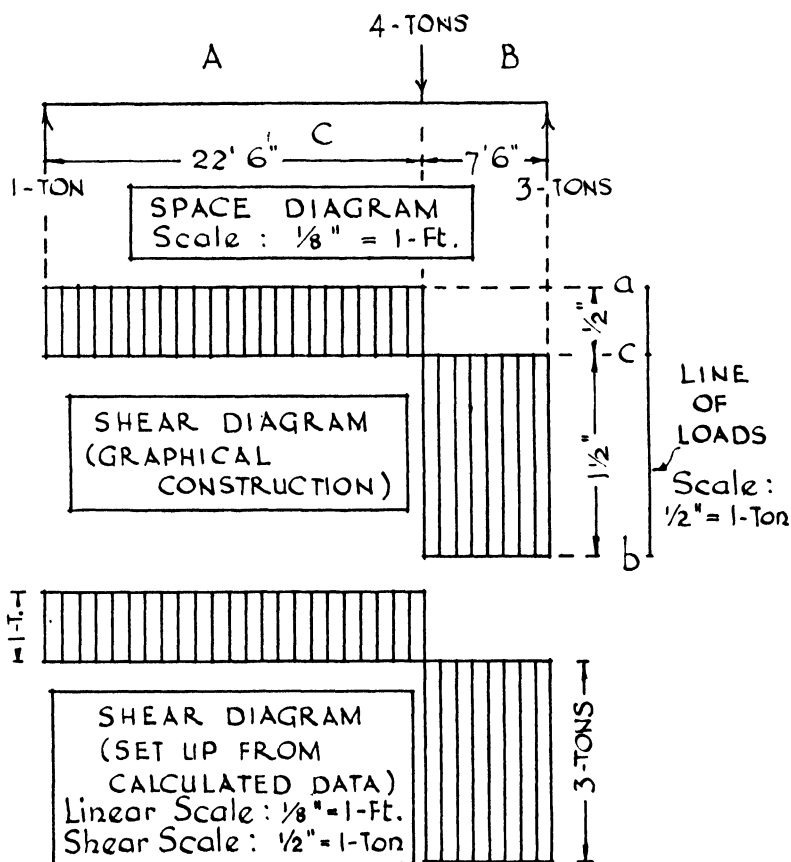


FIG. 213.—Beam with Non-Central Loads—Shear Diagrams.

It will be seen that in dealing with any case the bending moment and shear diagrams are best drawn at the same time, the polar diagram then serves a three-fold purpose, viz. :—To give the directions of the polar lines for the B.M. diagram, to give the amounts of the reactions, and to give the line of loads for the shear diagram.

**SUPPORTED BEAM WITH POINT LOAD NOT CENTRAL.**—Fig. 213 shows the shear diagram “set up” and also drawn graphically. In the graphical construction the reactions (the position of point *c*) would be found as previously shown, and this construction is not repeated here.

**SUPPORTED BEAM WITH SEVERAL POINT LOADS.**—After the previous cases Fig. 214 will be self-explanatory.

**BEAM OVERHANGING ONE SUPPORT.**—Fig. 215 gives the diagrams for this case. Each should be studied carefully as they appear to differ. Each, however, is produced by following the appropriate procedure and it is seen that the ordinates at all points are identical in both diagrams.

**BEAM WITH WHOLLY NEGATIVE MOMENTS.**—In this case the previous remarks also apply, as will be apparent from the two diagrams. (Fig. 216.)

**Shear-Bending Moment Relationship.**—If we study any one of these shear diagrams we find that, *at any point along the beam, the area of the diagram on either side of the point is equivalent to the magnitude of the B.M. at that point.* Thus, referring to Fig. 214, the bending moment at point *y*, 12-ft. from  $R_L$ , is 52·8-ft. tons. (See page 234.) The area of shear diagram to the left of this point is :—

$$\begin{aligned} \text{Area of end rectangle} &= 4\cdot9 \text{ tons (to force scale)} \times 10\text{-ft. (to} \\ &\quad \text{linear scale)} = 49\text{-ft. tons.} \end{aligned}$$

$$\text{Area of part small rectangle} = 1\cdot9 \text{ tons} \times 2\text{-ft.} = 3\cdot8\text{-ft. tons.}$$

$$\text{Therefore total area} = \underline{52\cdot8\text{-ft. tons.}}$$

Checking by considering the portion of diagram to the right of point *y* we get :—

$$\text{Area of end rectangle} = 5\cdot1 \text{ tons} \times 6\text{-ft.} = 30\cdot6\text{-ft. tons.}$$

$$\text{Area of next rectangle} = 3\cdot1 \text{ tons} \times 9\text{-ft.} = 27\cdot9\text{-ft. tons.}$$

$$\text{Area of part small rectangle} = -1\cdot9 \text{ tons} \times 3\text{-ft.} = \underline{-5\cdot7 \text{ ft. tons.}}$$

$$\text{Therefore total area} = 58\cdot5 - 5\cdot7 = \underline{52\cdot8\text{-ft. tons.}}$$

We also find that *the point of minimum shear is also the point of maximum bending moment.*

In the vast majority of cases a beam is a member which, for practical reasons, is of uniform *section* throughout its length. Bending and shearing stresses vary at different points along it, and a beam could therefore be designed so as to be of uniform *strength* throughout its length. An

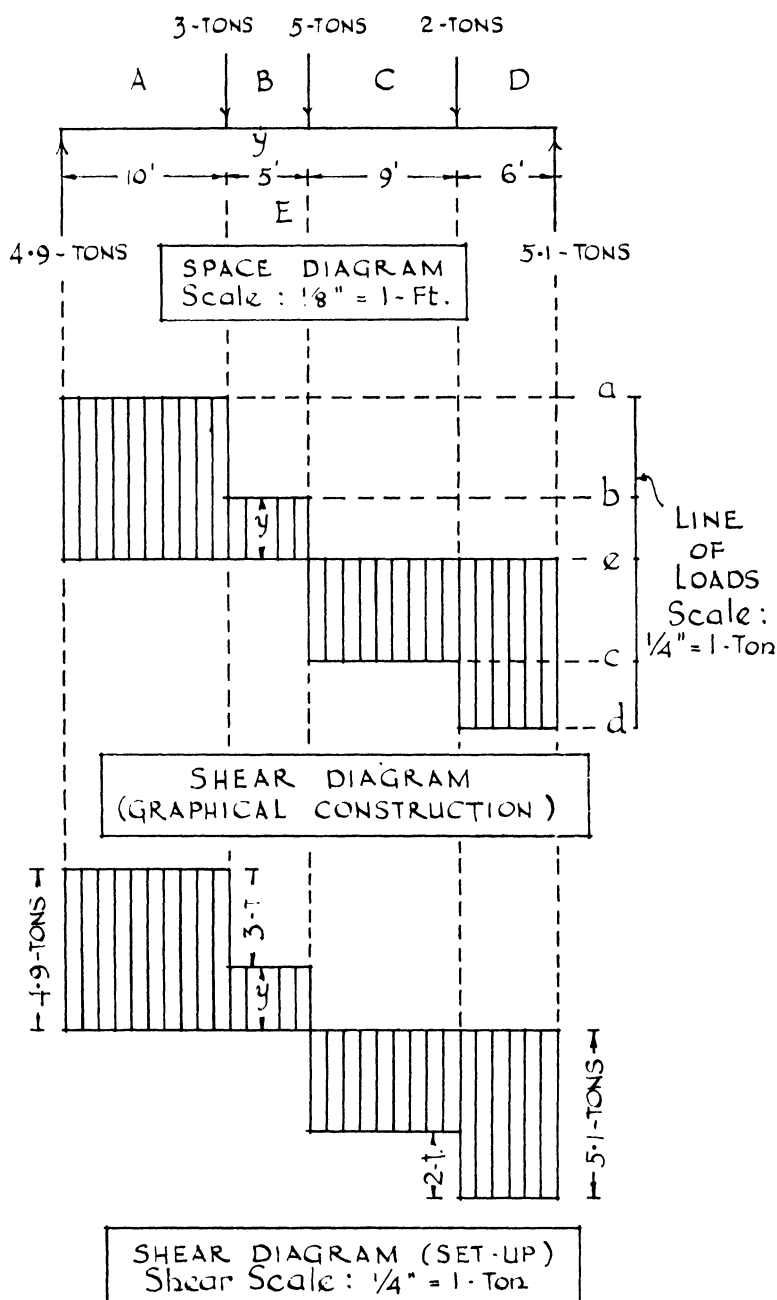


FIG. 214.—Beam with several Point Loads—Shear Diagrams.

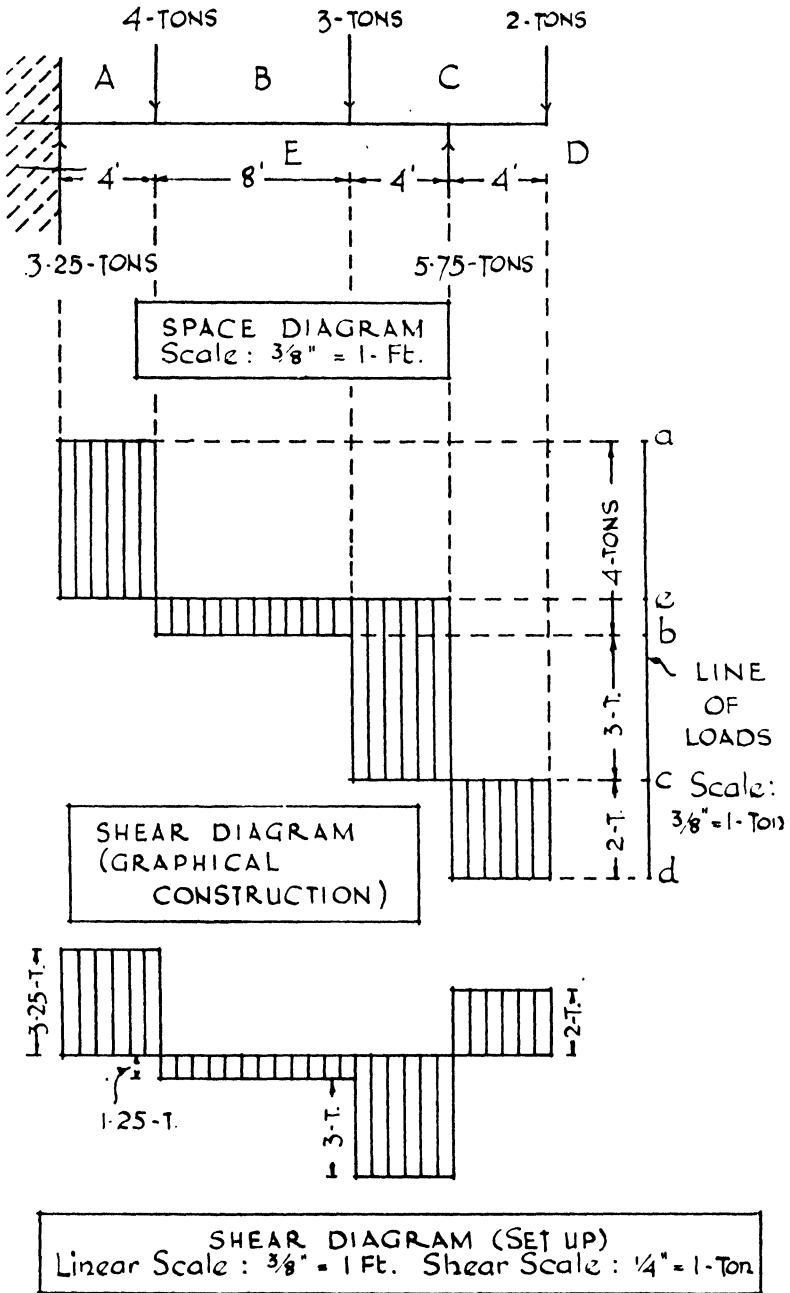


FIG. 215.—Beam overhanging One Support—Shear Diagrams.

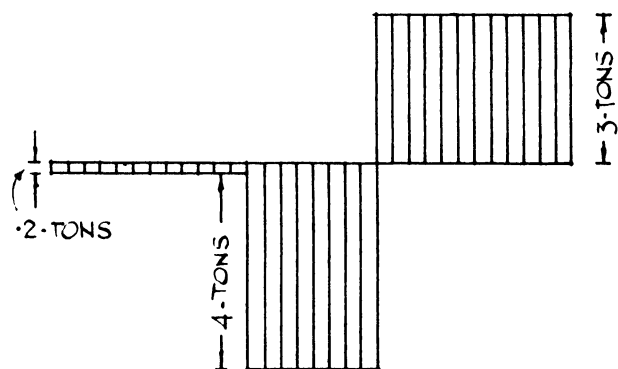
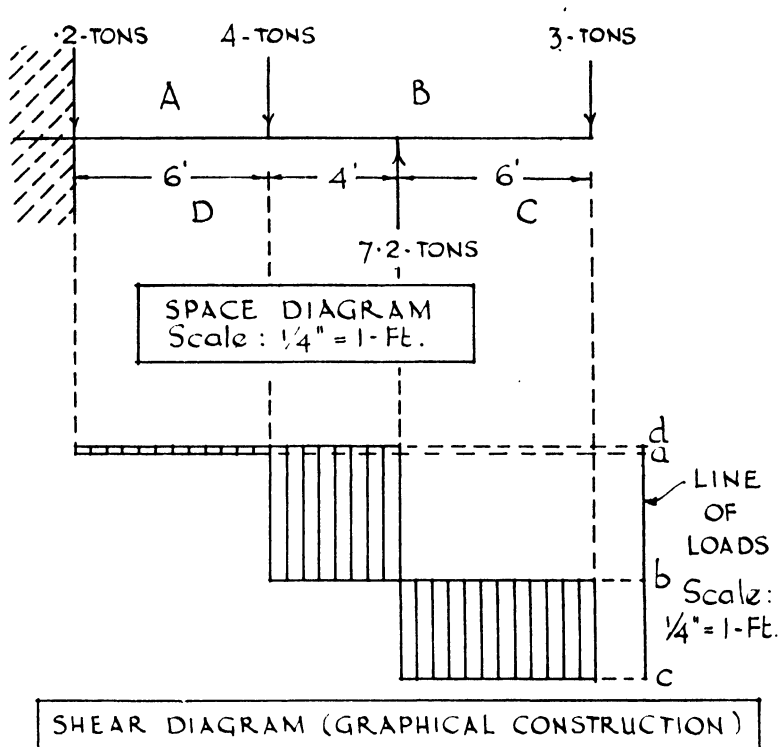


FIG. 216.—Overhanging Beam with Positive Reaction—Shear Diagrams.



approximation to this is seen in large steel plate girders such as are used in bridge work ; such girders are frequently deeper in the centre where bending stresses are greatest, than at the ends. Towards the ends they are more sturdy, with more stiffeners, thicker web, etc., because here the shearing stresses are greatest. But for ordinary spans and loads it would not be economical to vary the section. Timber sections are cut by sawing ; it is clear therefore that a uniform rectangular section is cheaper, and is produced in a shorter time, than one curved and carved in an attempt to produce a theoretically perfect beam. Its place and function in the construction also requires at least uniform depth. A steel beam is produced quickly by squeezing out a block of hot steel by passing it through pairs of rolls. Unless such a beam were of uniform section it would not be possible to use this method of production, and although less economical of metal it is more economical from the commercial standpoint than a cast beam.

From this it follows that most beams are extremely wasteful of material, since the section must be designed to be suitable at the points where the stresses are maximum. And, as in timber and steel beams we design to resist bending, only considering shear in cases where experience shows that it is desirable to do so, we need to know only the *maximum* B.M. But we do not want to calculate the B.M. at a number of points to see which is greatest (we may even then miss the *maximum* bending moment), nor do we want the trouble of drawing diagrams except in the less simple cases. What we do want is to be able to locate the point of maximum B.M. quickly and correctly, and this is done by finding the point of minimum shear. This, as already stated, is also the point of maximum bending moment.

To do this we need not actually draw the shear diagram, we can visualize it by observing the following rule :—*To find the position of maximum bending moment on a beam, subtract the loads in turn from either reaction until minus or zero is reached. When minus is reached the maximum bending moment occurs at that point. When zero is reached it occurs at all points between that point and the next load to be subtracted.*

Referring back to Fig. 214 let us apply the rule. Here we have to subtract 3 tons from  $R_L$  (4.9 tons) leaving 1.9 tons. The next load in order is 5 tons, and this from the remainder, 1.9 tons, gives a minus quantity. Our maximum B.M. therefore occurs at this point, and this may be verified from Fig. 188. Working from  $R_R$  we should of course obtain the same result.

The application of the second part of the rule is mainly in connection with “distributed” loads, loads which are spread over the whole or part of the span, and we are not dealing with these cases in the present volume. It does apply, however, to a beam which has point loads symmetrically

spaced such as the one shown in Fig. 217. This type of loading is used in experimental work where pure bending is under investigation, *i.e.* where no shear is permissible over some part of the span. Applying the rule to this case we reach zero immediately and then have maximum bending moment extending over the distance between the loads. There is of course complete absence of shear along this length of beam.

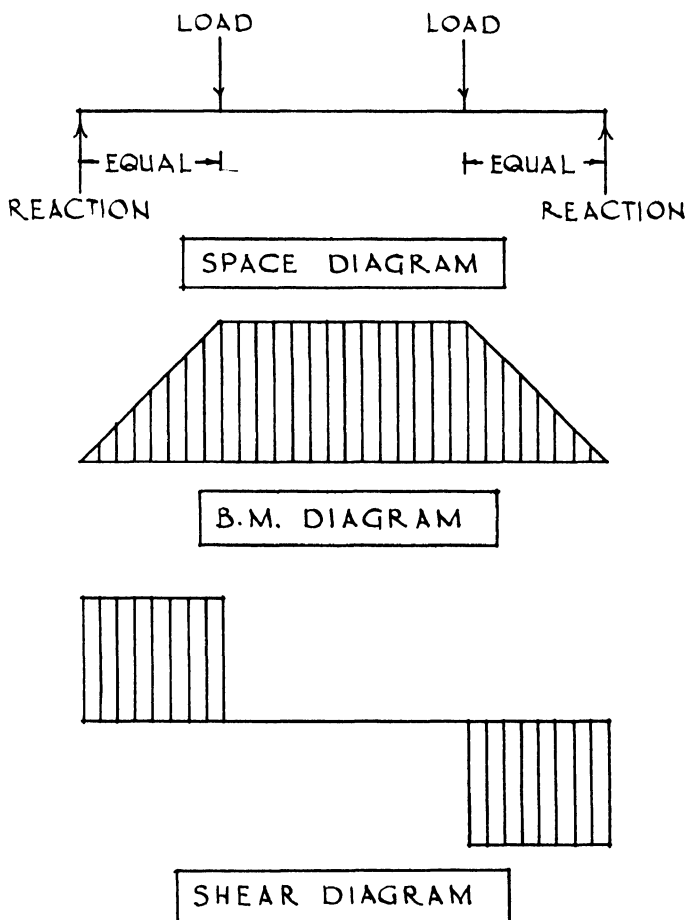


FIG. 217.—Symmetrically Loaded Beam—B.M. and Shear Diagrams.

#### 4. RESISTANCE TO BENDING.

We have investigated at some length the forces and moments acting upon simple beams, and although the design of beams cannot be attempted in detail at this stage, it is proposed now to give a broad explanation of their effects upon the beam. It is clear that, for equilibrium, the material of which the beam is composed must resist the external forces, but this resistance cannot be such a simple matter as in the cases discussed in

Chapter XIV. Experiment 123 demonstrated shearing stresses in a cantilever, and our various shear diagrams have shown how all beams suffer such stresses. We have also seen the nature of transverse stress (page 202) and we must now investigate the nature of this in more detail.

EXPERIMENT 126.—To show tensile and compressive stress in a beam.

Fig. 218, A, shows a length of 2-in.  $\times$  1½-in. timber with sawcuts at close intervals along top and bottom. This is to be used as an experimental beam. Support the beam over a 2-ft. span and suspend a weight at the centre as at B. The beam is seen to bend, and in doing so the sawcuts on the upper surface close, showing compression, whilst those on the lower surface open, showing tension.

Arranged as a cantilever at C, the compression and tension are reversed.

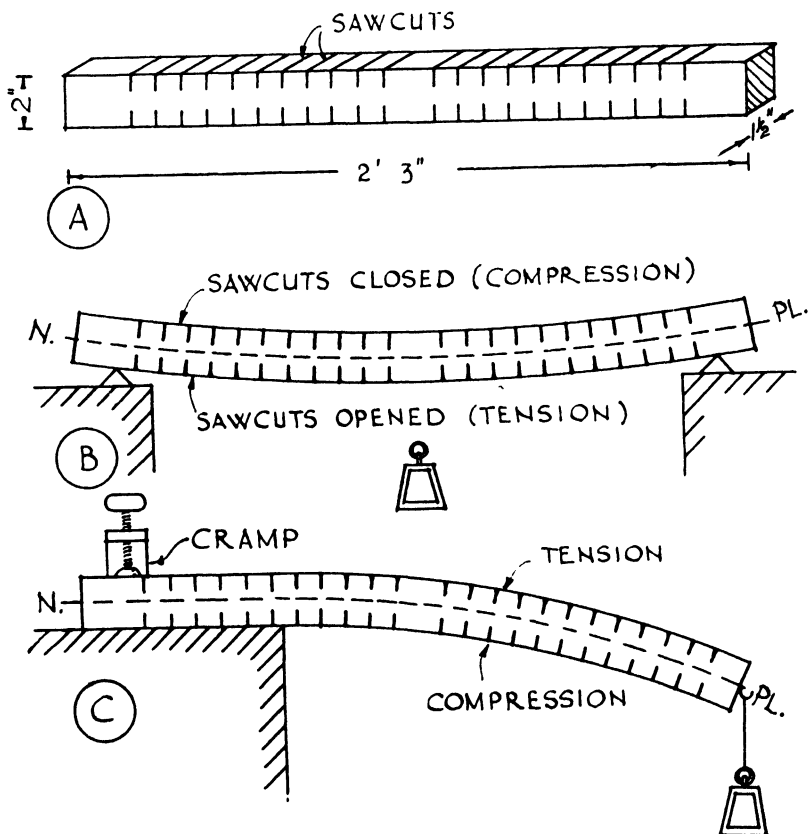


FIG. 218.—Showing Tension and Compression produced by Bending.

In both these cases the strain, and consequently the stress, changes from compression to tension in the depth of the beam. The plane of the beam (horizontal before bending) at which the changeover occurs is called the *neutral plane*, and for a rectangular section is at mid-depth. At all

sections along this plane no transverse strain and no transverse stress occur ; this may be verified by drawing a straight line along the face of the beam, halfway down, then loading as a beam and measuring the new lengths of the upper edge, the lower edge and this midway line. This line will remain its original length, the upper edge will have become shorter and the lower edge longer.

Fig. 219 shows this neutral plane (2 dimensions) in the beam and also the corresponding line or axis (1 dimension) in the cross-section. When referring to a cross-section of the beam (which is a plane figure) we therefore refer to the *neutral axis*. We shall see later how the bending stress is distributed over the cross-section ; in the meantime let us see how the tensile and compressive stresses act in resisting the external forces.

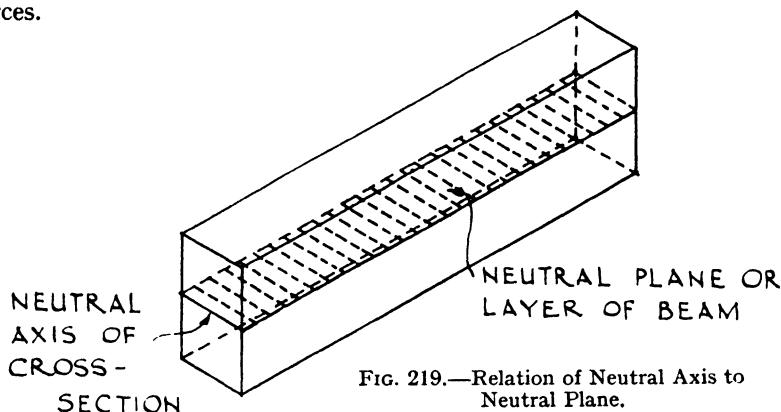


FIG. 219.—Relation of Neutral Axis to Neutral Plane.

**EXPERIMENT 127.**—To show the balance of moments in a cantilever.

The apparatus used in Experiment 123 is again used, but the two horizontal struts are replaced by two diagonal struts as in Fig. 220. Before applying the load adjust the spring balance so that the end block of the cantilever is true. The balance reading, 1.5-lb., will then be called zero. Now apply the load of 4-lb. It will be seen that the two chains at the top of the cantilever take the tension, but the two struts at the bottom, which in Experiment 123 took the compression, are now missing and their place is taken by the spring balance. Readjust the balance until equilibrium is restored and note the new reading, 7-lb. This, minus zero, gives the magnitude of the compression, 5.5-lb., which may be shown to be equal to the tension in the chains.

Let us now consider the equilibrium of the end block of the cantilever. Taking moments about the upper point *a* we have :—

$$\begin{aligned}\text{Clockwise moment} &= \text{Load (4-lb.)} \times \text{leverage 1. (5.5-in.)} \\ &= \underline{22\text{-in.-lb.}}\end{aligned}$$

$$\begin{aligned}\text{Anti-clockwise moment} &= \text{Compression (5.5-lb.)} \times \text{leverage 2. (4-in.)} \\ &= \underline{22\text{-in.-lb.}}\end{aligned}$$

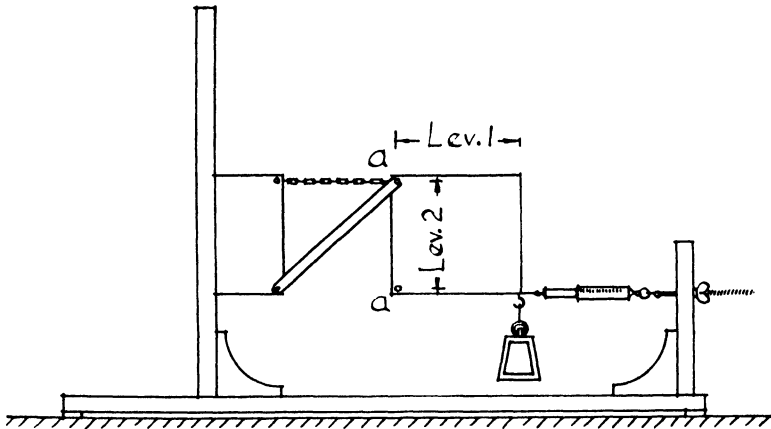


FIG. 220.—Balance of Moments in Cantilever—Experimental Treatment.

Fig. 221 shows this diagrammatically for any cantilever.

$W$  = the load.

$l$  = the distance to the section under consideration.

$S$  = the vertical shear across that section.

$T$  = the Tension (assumed to be acting at the extreme top plane of the cantilever).

$C$  = the Compression (assumed to be acting at the extreme bottom).

$a$  = the vertical distance between  $T$  and  $C$  (assumed to be the depth of the cantilever).

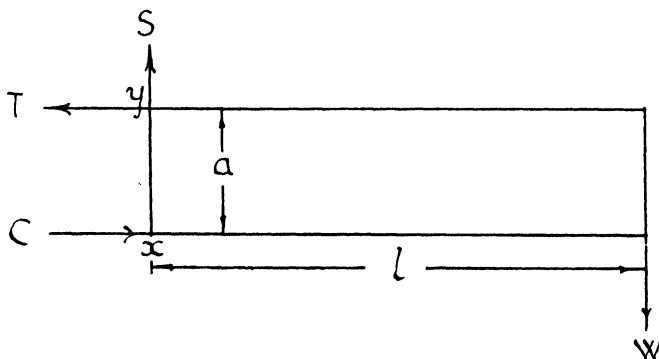


FIG. 221.—Moment of Resistance of Cantilever.

The cantilever is in equilibrium, therefore all forces acting are balanced and all moments are balanced. The only external force is  $W$  and this is balanced by  $S$ , the resistance to vertical shear offered by the material at this section. These two thus constitute a couple, and their

effect is a tendency for the portion of cantilever to rotate clockwise. Now  $T$  and  $C$  are also a couple, but tending to cause rotation anti-clockwise, and obviously it is the balance of these two couples which produces equilibrium. They must therefore be equal to each other.

Let us take moments about point  $x$ . Both  $S$  and  $C$  pass through  $x$  and thus the moment of each is zero.

Therefore  $W \times l$  (clockwise) =  $T \times a$  (anti-clockwise).

Now  $(W \times l)$  will be recognized as the bending moment, B.M. and  $(T \times a)$  is the resisting moment or *moment of resistance* (symbol M.R.)

If we take moments about point  $y$ , then  $S$  and  $T$  produce no moment. Therefore  $W \times l = C \times a$ .

Thus  $(T \times a) = (C \times a)$ , and  $T = C$ .

From this we get the statement B.M. = M.R.

Fig. 222 shows a beam carrying a central point load. Considering only one side of the section we have, as in the case of the cantilever :—

$$\text{B.M.} = \frac{W}{2} \times \frac{l}{2} = \frac{Wl}{4}.$$

$$\text{M.R.} = C \times a \text{ or } T \times a$$

and B.M. = M.R. as before.

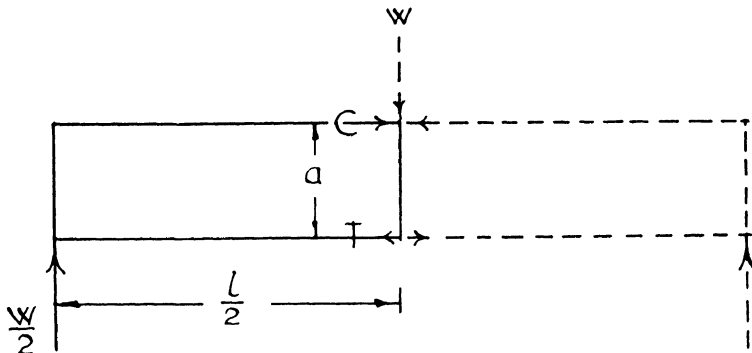


FIG. 222.—Moment of Resistance of Beam.

**STRESS DISTRIBUTION.**—Fig. 223 shows the cross-section of a rectangular beam 12-in. deep and 6-in. wide, with the neutral axis at mid-depth. When the beam is supported at its ends, and is carrying loads, the stresses due to bending are compression in the upper half and tension in the lower half. The compression is maximum in a plane at the extreme top, the tension is maximum at the extreme bottom, and at the neutral axis compression and tension change over and consequently no stress occurs.

We may represent this graphically as in Fig. 224 where, assuming the maximum compression to be .5 tons per sq. in., it may be represented

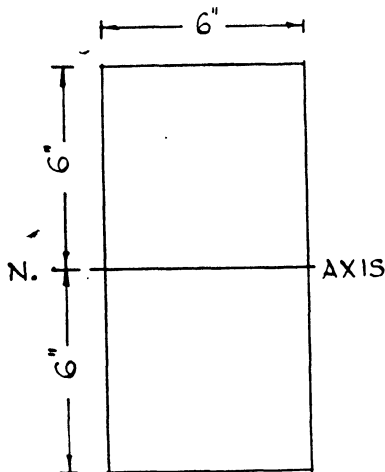


FIG. 223.—Cross-Section of "Rectangular" Beam.

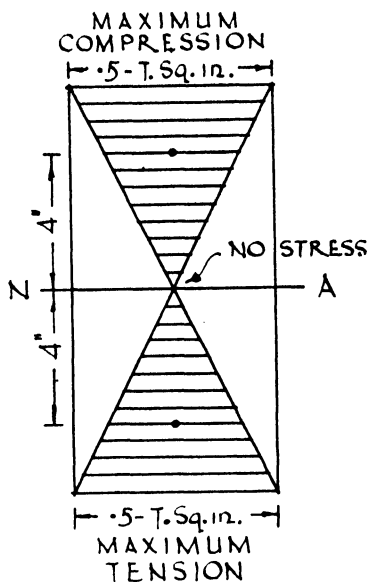


FIG. 224.—Stress-Distribution Diagram—Rectangular Section.

by the full width of the section. At the neutral axis it is represented by a point only, and in horizontal planes at intermediate depths it varies as shown. Similarly the triangle in the lower half of the section represents the intensity of tensile stress varying from maximum at the extreme layer to zero at the neutral axis.

We may thus consider the stress to act at its maximum intensity of .5 tons per sq. in. over the area of the two shaded triangles. This shaded area is called the *equivalent inertia area* or the *resistance area*, and as the beam is of a single material of uniform strength it will be seen that *from considerations of bending only* (ignoring shear stress) the unshaded portions of the section could be omitted. If this were done the section would approximate to the normal rolled steel H section.

**MOMENT OF RESISTANCE.**—The total compression, C, and the total tension, T, are each therefore:—

$$\begin{aligned} C \text{ and } T &= \text{Intensity of stress} \times \text{area} \\ &= .5 \text{ tons per sq. in.} \times \text{area of shaded triangle.} \\ &= .5 \times \frac{6 \times 6}{2} = \underline{9 \text{ tons.}} \end{aligned}$$

In Figs. 221 and 222, C and T are shown acting at the extreme layers of the section. This was assumed for simplicity at that stage but it will now be clear that, for the purpose of determining the actual moment of resistance of the section, the lever arm *a* is not the full depth of the beam

but the distance between the points at which C and T act. The equivalent point at which C may be assumed to act is the geometrical centre (the Centroid—see next chapter) of the compression triangle, and this lies on the vertical centre line 4-in. above the neutral axis. The total tension acts similarly at a point 4-in. below the neutral axis. The lever arm is thus 8-in. as in Fig. 225 and the magnitude of the moment of resistance, M.R., is thus  $C$  (or  $T$ )  $\times a = 9$  tons  $\times 8$ -in. = 72-in. tons.

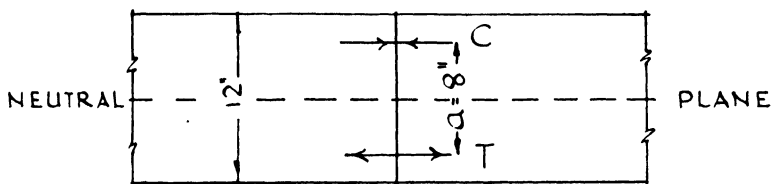


FIG. 225.—Lever Arm of Tension and Compression in Beam Section.

Now, as for equilibrium,  $M.R. = B.M.$  this beam section is suitable to resist a bending moment of 72-in. tons, for example when used as a cantilever or beam under any conditions of span, load, etc., such as would produce a bending moment of this amount. Note that this is only the case when the intensity of stress, compression and tension, is .5 tons per sq. in. If the same section were used for a beam the material of which was capable of being stressed to 1 ton per sq. in., its M.R. would be 144-in. tons because in such a case the total  $C$  and  $T$  would be 18 tons.

This, the M.R. of any section for unit stress (say 1 ton per sq. in.), is called the “modulus” of the section or *section modulus* ( $Z$ ). If we know the section modulus for a particular section we can therefore find its M.R. for any intensity of stress.

Thus  $M.R. = \text{intensity of stress} \times \text{section modulus} = f \times Z$ .

In designing a timber beam for any given conditions we must first determine the maximum B.M. Our beam must have a M.R. at least equal to this. We know the maximum permissible intensity of stress,  $f$ . All that remains is to determine  $Z$ , and this resolves itself into finding a suitable rectangle having this value of  $Z$ . This problem is dealt with in the next chapter.



## PROPERTIES OF SECTIONS

1. *Centroid.*
2. *Moment of Inertia.*
3. *Radius of Gyration.*
4. *Section Modulus.*

Under direct stress, tension or compression,  $W = f \times A$ , or total stress = intensity of stress  $\times$  area. In such a case the *shape* of the area is immaterial, thus if we have determined the required sectional area for a steel tie bar we may select a round bar, a square bar, a flat bar or any other type of member, even a chain, which has the required sectional area. In the case of a compressional member its slenderness must be taken into account, for this affects  $f$ , but still  $W = f \times A$ . In members subjected to bending, however, the shape is as important as the sectional area because we have to provide a *moment*, the moment of resistance, M.R.

The various properties dealt with in this chapter are some of those utilized in the design of members subjected to bending stresses, such as beams, slender pillars or struts, walls, foundations, and on occasion entire structures. It should be clear that these properties are properties of sections or surfaces, in other words plane geometrical figures such as squares, circles, etc. These are the shapes of the cross-sections or surfaces of structural members which themselves are solids. Thus a rectangle is a plane figure which has certain well-known properties. It has a length, a breadth, an area and so on. It also has a *centroid*, a *moment of inertia*, a *section modulus*, etc. It is with these not-so-obvious properties that we are concerned in this chapter, although the use to which some of them are put may not be clear until a more advanced stage has been reached.

### 1. CENTROID.

Just as we can have a moment of a force, or of a system of forces, about any point or line so it is convenient for certain purposes to consider the moment of an area or figure.

If A B C D, Fig. 226, is a plane figure having a certain area we can find its moment about any point or line, say line O—O. Such a line is referred to as an *axis*, and the moments about any points in the axis are clearly equal. Now the area of a figure may be considered to be composed of a number of smaller areas, the smaller the areas the greater the number. The largest number of these areas we can conceive is an infinite number, and then the areas are infinitely small.

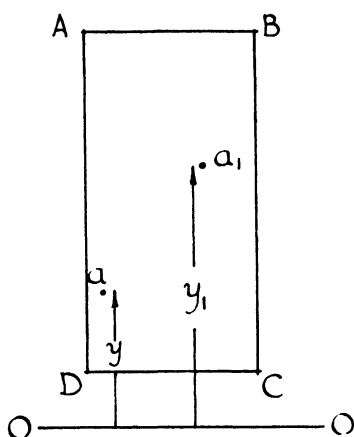


FIG. 226.—First Moment of a Figure.

is chiefly in the determination of the centroid of the figure. If, instead of axis O—O, we consider moments of area about an axis passing

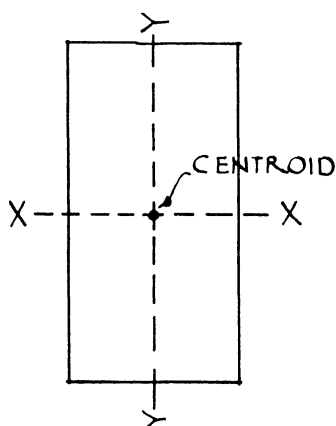


FIG. 227.—Centroid of a Figure.

Let us then consider the figure to be composed of an infinite number of infinitely small “particles” of area, which we may name  $a$ ,  $a_1$ ,  $a_2$ , etc., situated at perpendicular distances from the axis of  $y$ ,  $y_1$ ,  $y_2$ , etc., respectively. Then the moment of particle  $a$  about axis O—O is  $a \times y$ , that of particle  $a_1$  is  $a_1 \times y_1$ , etc. When we have an infinite number of such moments the total or “summation” of them all is expressed  $\Sigma ay$ , and this is the *first moment* of figure A B C D about axis O—O.

This first moment is of course a property of the figure but its use through the figure itself we get two types of moment according to whether the particles of area are situated above or below the axis. Calling these positive and negative respectively it is clearly possible to have the axis in such a position that the sum of the positive moments is equal to the sum of the negative moments, in other words so that  $\Sigma ay = 0$ . In such a case the axis bisects the area, as axis X—X in Fig. 227. If we similarly have a second axis about which  $\Sigma ay = 0$ , such as Y—Y, then at the intersection of the two axes is a *point* about which  $\Sigma ay = 0$ . This point is called the *centroid* of the figure.

The first moment of a figure about an axis passing through its centroid is therefore zero, and the *centroid of a figure is the point about which the sum of the moments of all the particles of area contained in the figure is zero.*

The centroid of a figure corresponds to the centre of gravity (C.G.) of a solid, but the two should not be confused. It is clearly impossible for a plane figure to have a C.G. for it has no mass and thus cannot be acted upon by gravity. But if we have a solid of uniform thickness we can determine the centroid of its surface by finding the C.G. of the solid.

**EXPERIMENT 128.**—To find the centroid of an irregular figure.

Draw the figure on thin sheet metal, card or wood and cut it out. This is a solid, affected by gravity, and we determine its C.G. in the following manner :—

Fix three pins in the face of the solid approximately equidistant around the periphery. Suspend the solid from each pin in turn, at the same time suspending a plumb-line from the pin. Then the solid is in equilibrium, on each occasion, under the action of two forces—its weight acting downwards and the reaction at the hook acting upwards. Then the plumb-line represents an axis which bisects the area, and the first moment of the area about the line is zero. The centroid therefore lies on this line. It lies similarly on the other lines when suspended by the other pins, therefore the centroid lies at their intersection. Two points of suspension are sufficient, but the third acts as a check.

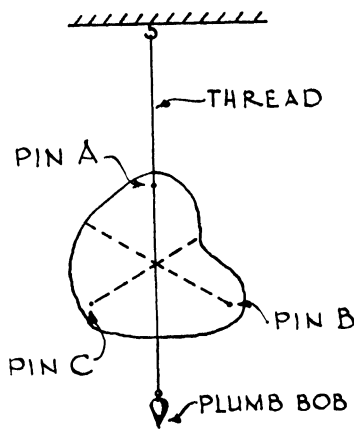


FIG. 228.—Centroid of Irregular Figure—Experimentally.

What we have found in this experiment is really the end of a line passing through the body perpendicular to the face, and at the centre of which lies the C.G. of the body.

**Centroids of Common Figures.**—Certain figures are common as cross-sections and their centroids are found geometrically in various ways, some of which are given.

**CENTROID OF A TRIANGLE.**—If a triangle be assumed divided into a

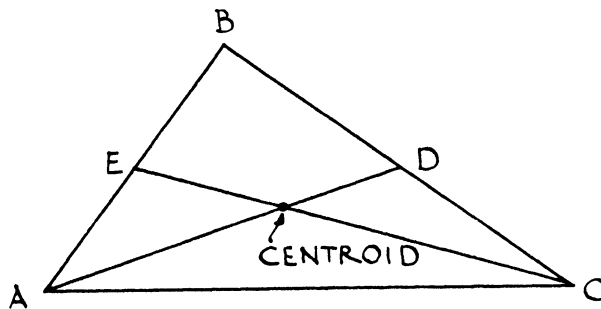


FIG. 229.—Centroid of Triangle.

number of infinitely thin strips parallel to one side, then the centroid of each strip will lie at its centre, and they will all lie on the median or line bisecting that side, as AD and CE (Fig. 229). The

centroid of the triangle thus lies at the intersection of two such medians. Its height from the base is one-third of the altitude of the triangle, and from this is derived another method of locating the centroid.

**CENTROID OF A RECTANGLE.**—We have seen that the centroid of a rectangle is at the intersection of two axes each bisecting opposite sides, as in Fig. 227. Its position is also given with slightly less trouble as the point of intersection of the two diagonals of the rectangle, as in Fig. 230. Both these constructions apply to any parallelogram.

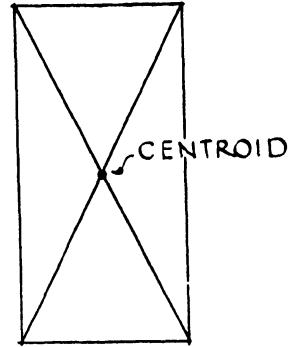


FIG. 230.—Centroid of Rectangle.

**CENTROID OF A TRAPEZIUM.**—In Fig. 231, AB and CD are parallel sides. The centroid must therefore lie on line EF joining the centres of AB and CD. Produce AB to G so that BG equals CD, produce CD to H so that DH equals AB, and join HG. Then EF and HG intersect at a point which is the centroid of the trapezium.

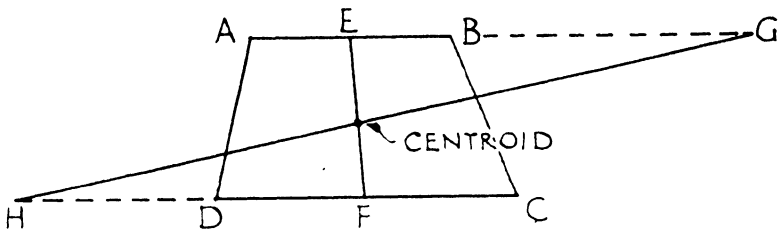


FIG. 231.—Centroid of Trapezium.

As an alternative the centroid may be found by the construction shown in Fig. 232, in which AE and BG are equal to CD, and DH, CF are equal to AB. EF and HG then intersect at the centroid.

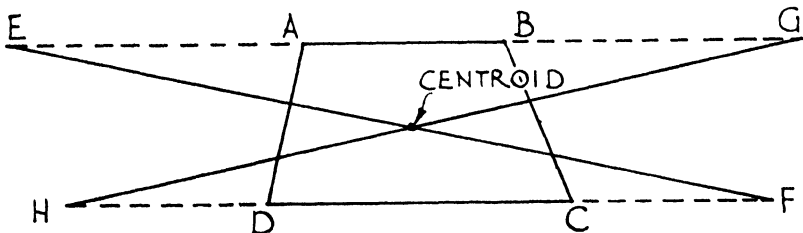


FIG. 232.—Centroid of Trapezium—Alternative Method.

**CENTROID OF ANY QUADRILATERAL.**—ABCD is a quadrilateral (Fig. 233). Draw the diagonals AC, BD intersecting in E. Along CA mark off CF equal to AE. Join DF, BF. Then the centroid of triangle DBF is also the centroid of the whole figure.

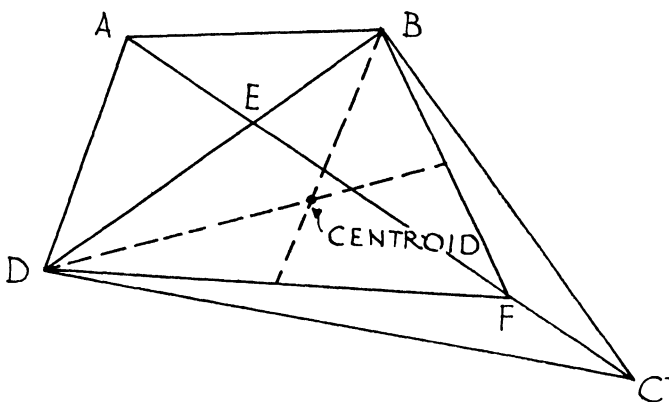


FIG. 233.—Centroid of any Quadrilateral.

**CENTROID OF ANY POLYGON.**—Let ABCDE be the polygon of which the centroid is required. Divide the figure into triangles, say as in Fig. 234.

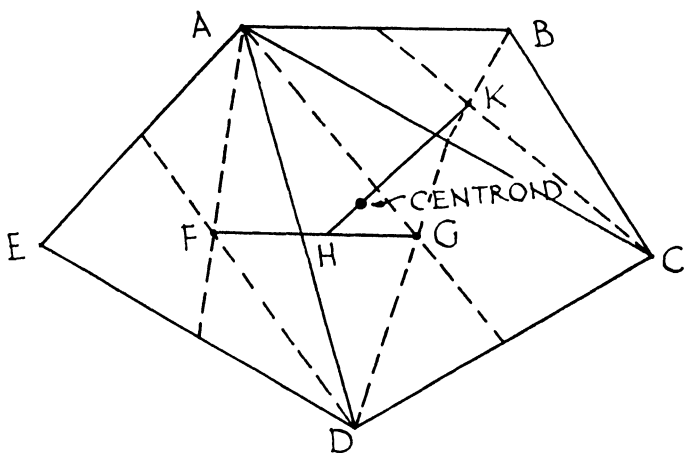


FIG. 234.—Centroid of any Polygon.

Find F, the centroid of triangle EAD and G, the centroid of triangle ACD. Join FG. Next calculate the areas of EAD and ACD, say 6 and 8 units respectively. Divide FG into  $6 + 8 = 14$  equal parts. Then point H, 8 parts from F or 6 parts from G, is the centroid of figure ACDE.

Join H to K, the centroid of ABC, find the area of ABC, say 5 units, and divide HK into  $14 + 5 = 19$  equal parts. Find a point 5 parts from H or 14 parts from K—this is the centroid of the whole figure.

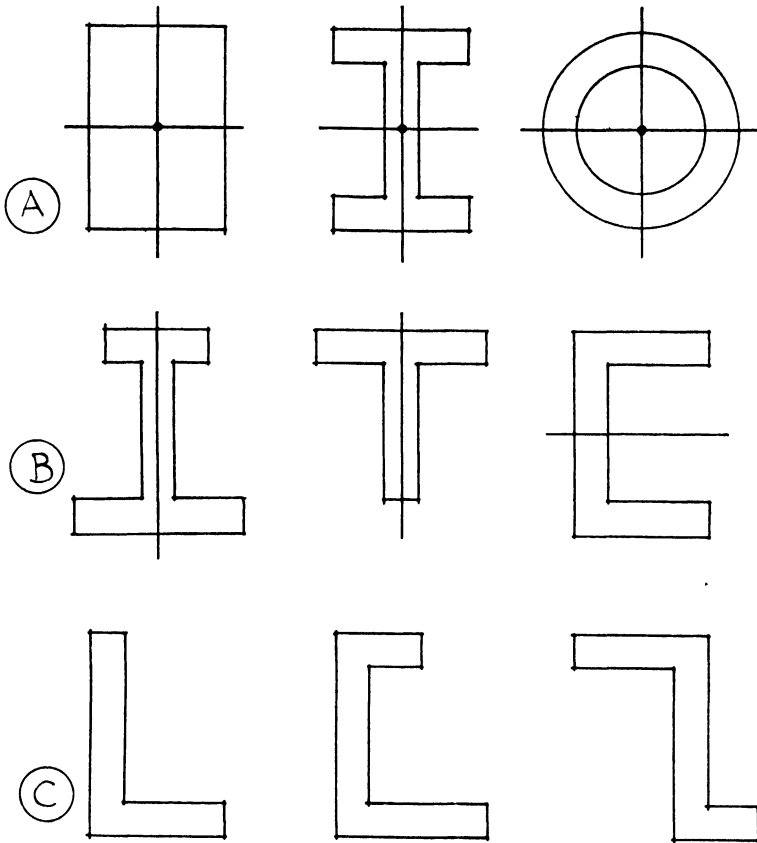


FIG. 235.—Centroids of Common Structural Shapes :—

- A. Figures symmetrical about Two Axes.
- B. Figures symmetrical about One Axis.
- C. Asymmetrical Figures.

**AXES OF SYMMETRY.**—If a figure is symmetrical about an axis its centroid lies on that axis, and if it is symmetrical about two axes the centroid lies at their intersection. An axis of symmetry will invariably be apparent from inspection.

**CENTROIDS BY MOMENTS.**—As with a system of forces, we may consider the moments of the *areas* of component parts of a figure and so find the centroid distance from any point or axis. This is especially the case with structural sections which are, or approximate to, regular figures.

Consider the figure shown in Fig. 236. As the figure is symmetrical about axis X—X the centroid lies on this axis. It is therefore only necessary to find its position, say with reference to the side AB. Divide the figure into the three rectangles as shown. Then, for the purpose of finding moments, the area of each rectangle may be considered concentrated at its respective centroid.

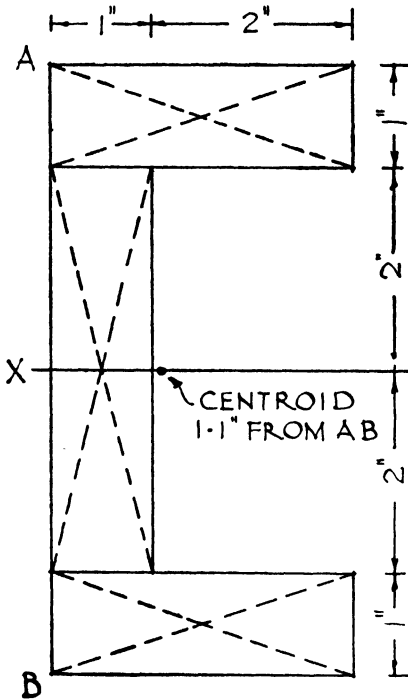


FIG. 236.—Centroid of Channel Section by Moments.

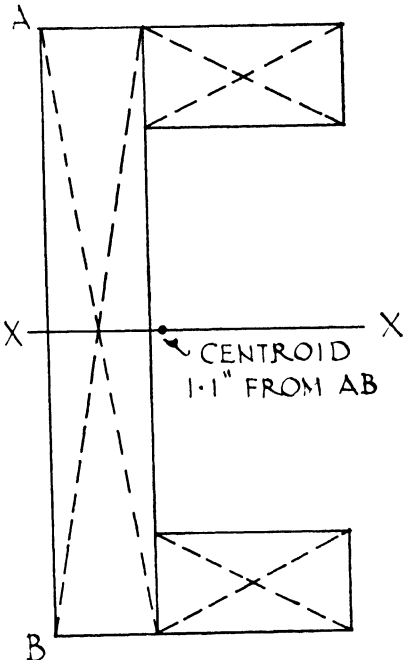


FIG. 237.—Centroid of Channel Section—Alternative Method.

Taking moments about AB we have :—

$$2 [(3\text{-in.} \times 1\text{-in.}) \times 1.5\text{-in.}] + (4\text{-in.} \times 1\text{-in.}) \times .5\text{-in.} \\ = 9 + 2 = 11\text{-in.}^3$$

Balancing this we have :—

$$\text{The area of the whole figure} \times \text{its centroid distance.} \\ = 10\text{-in.}^2 \times x\text{-in.}$$

$$\text{Therefore } x = \frac{11\text{-in.}^3}{10\text{-in.}^2} = \underline{1.1\text{-in.}}$$

In other words the centroid is 1.1-in. along X—X from side AB.  
(Note that the centroid of a figure may lie outside the figure.)

In Fig. 237 is seen an alternative way of dividing the figure. In this case the centroid distance

$$x = \frac{(6\text{-in.} \times 1\text{-in.}) \times .5\text{-in.} + 2 [(2\text{-in.} \times 1\text{-in.}) \times 2\text{-in.}]}{10\text{-in.}^2}$$

$$= \frac{3 + 8}{10} = \frac{11\text{-in.}^3}{10\text{-in.}^2} = \underline{1.1\text{-in.}} \text{ as before.}$$

As a check we may employ the method indicated in Fig. 238. Assuming the areas to be forces acting downwards, ascertain whether they balance about the centroid.

Thus, taking moments about  $x$  :—

$$6\text{-in.}^2 \times 6\text{-in.} = 4\text{-in.}^2 \times 9\text{-in.}$$

$$36\text{-in.}^3 = 36\text{-in.}^3$$

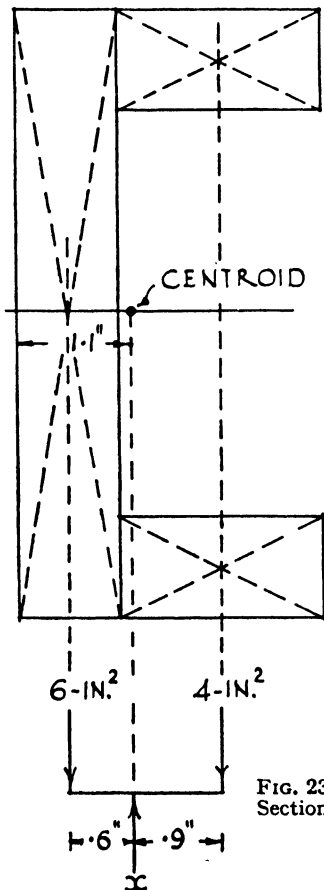


FIG. 238.—Centroid of Channel Section—Method of Checking.

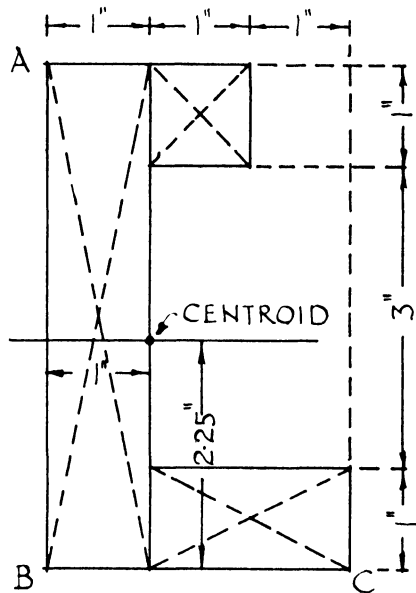


FIG. 239.—Centroid of Irregular Channel Section by Moments.



In Fig. 239 we have an asymmetrical figure, and we have therefore to find the centroid distance from two axes at right-angles to each other, say AB, BC.

Taking moments about B along BC :—

$$\begin{aligned} & [(5\text{-in.} \times 1\text{-in.}) \times 5\text{-in.}] + [(2\text{-in.} \times 1\text{-in.}) \times 2\text{-in.}] \\ & + [(1\text{-in.} \times 1\text{-in.}) \times 1.5\text{-in.}] = 8\text{-in.}^2 \times x \\ & 2.5 + 4 + 1.5 = 8x \end{aligned}$$

$$\text{Therefore } x = \frac{8\text{-in.}^2}{8\text{-in.}^2} = 1\text{-in. from AB.}$$

Taking moments about B along BA :—

$$\begin{aligned} & [(2\text{-in.} \times 1\text{-in.}) \times 5\text{-in.}] + [(5\text{-in.} \times 1\text{-in.}) \times 2.5\text{-in.}] \\ & + [(1\text{-in.} \times 1\text{-in.}) \times 4.5\text{-in.}] = (8\text{-in.}^2 \times x) \\ & 1 + 12.5 + 4.5 = 8x \end{aligned}$$

$$\text{Therefore } x = \frac{18\text{-in.}^2}{8\text{-in.}^2} = \underline{2.25\text{-in. from B.C.}}$$

Checking the distance from AB (Fig. 240, A) :—

$$\begin{aligned} (5\text{-in.}^2 \times 5\text{-in.}) &= (1\text{-in.}^2 \times 5\text{-in.}) + (2\text{-in.}^2 \times 1\text{-in.}) \\ 2.5\text{-in.}^3 &= 2.5\text{-in.}^3 \end{aligned}$$

Checking the distance from BC (Fig. 240, B) :—

$$\begin{aligned} (1\text{-in.}^2 \times 2.25\text{-in.}) + (5\text{-in.}^2 \times .25\text{-in.}) &= (2\text{-in.}^2 \times 1.75\text{-in.}) \\ 3.5\text{-in.}^3 &= 3.5\text{-in.}^3 \end{aligned}$$

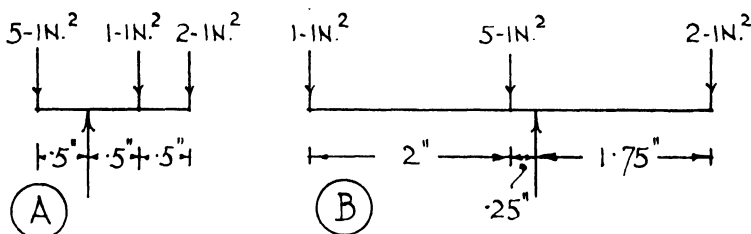


FIG. 240—Centroid of Irregular Channel Section—Method of Checking.

**CENTROIDS BY GRAPHICAL METHOD.**—Determining the centroid of a figure is a similar problem to finding the resultant of a system of forces, and the funicular diagram method may therefore be employed. In Fig. 241 is given the construction for locating the centroid of the figure shown in Fig. 236, whilst Fig. 242 applies to the figure given in Fig. 239.

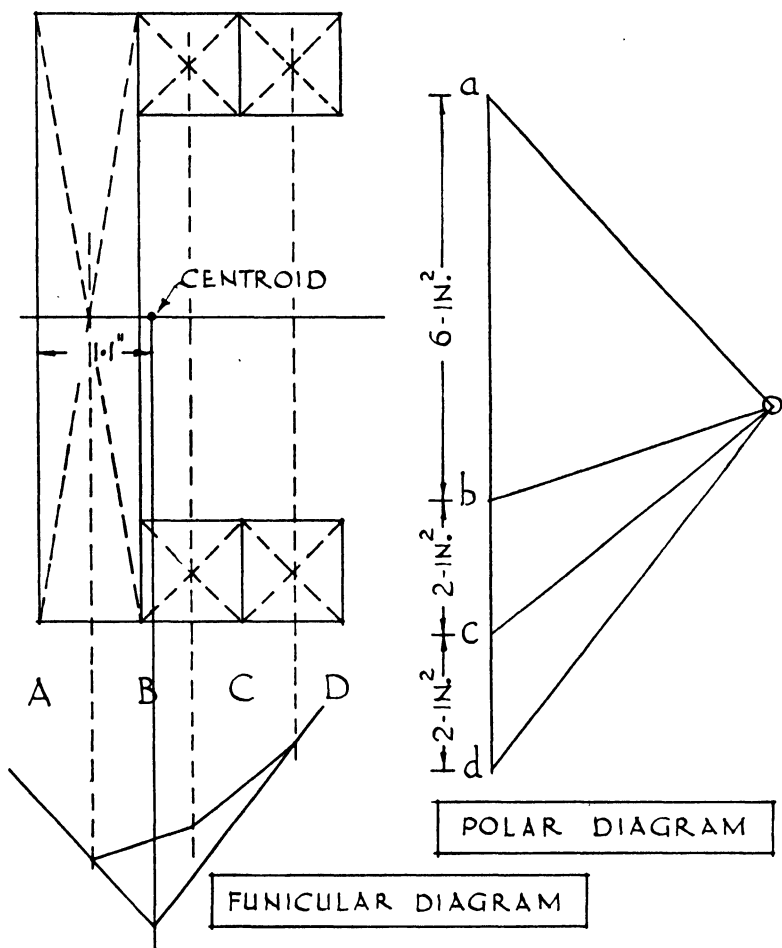


FIG. 241.—Centroid of Channel Section—Graphical Solution.

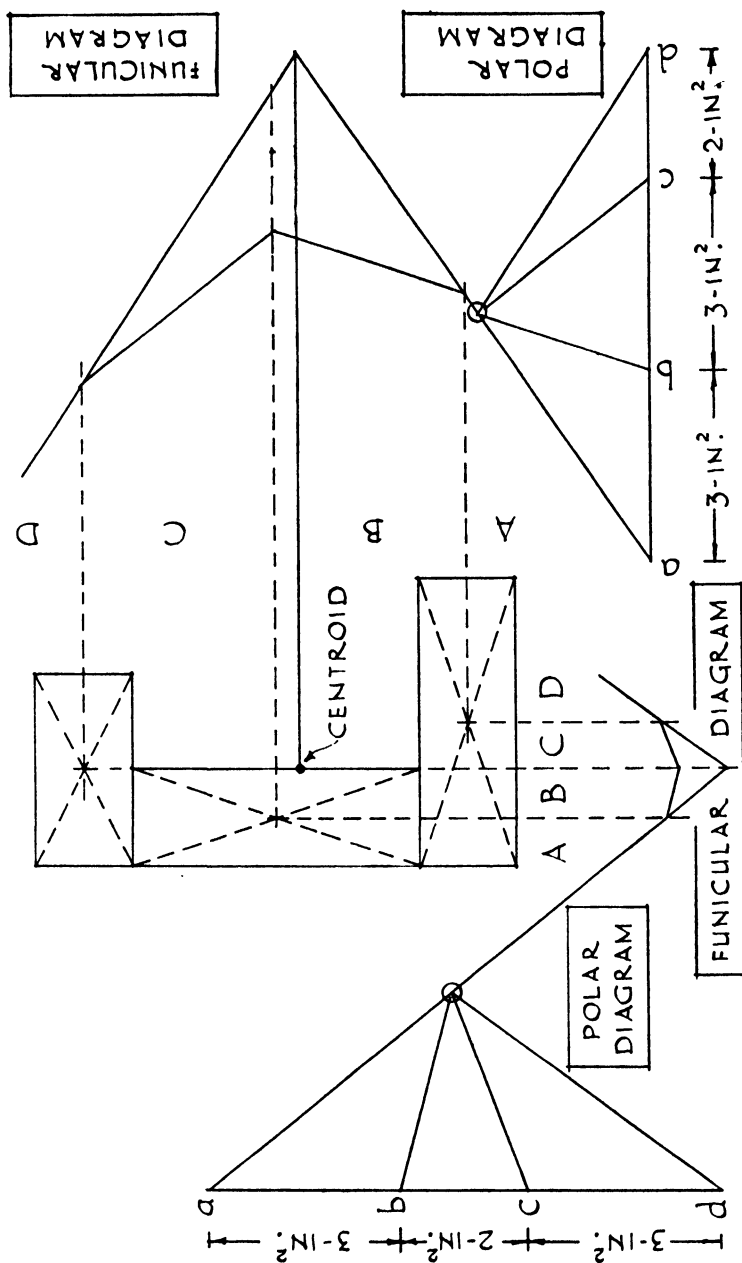


Fig. 242.—Centroid of Irregular Channel Section—Graphical Solution.

## 2. MOMENT OF INERTIA.

The *moment of inertia* of a body is a property used in dynamics and strictly speaking is a misnomer when applied to a plane figure. For this reason it is sometimes referred to as the *second moment* of area. Its symbol is  $I$ .

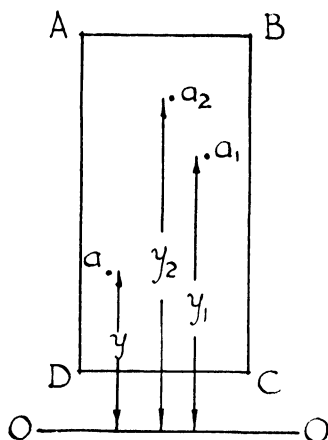


FIG. 243.—Moment of Inertia of a Figure.

If ABCD be a plane figure (Fig. 243) in which  $a, a_1, a_2$ , etc. are infinitely small "particles" of area, and  $y, y_1, y_2$ , etc. their respective distances from an axis, then  $(a \times y^2) + (a_1 \times y_1^2) + (a_2 \times y_2^2)$ , etc., etc.  $= \Sigma ay^2 =$  the moment of inertia or second moment of the figure about the axis. The reason for the name *second moment* will be apparent if we refer to Fig. 226 where we found that the *first moment* was  $\Sigma ay$ .

The moment of inertia of a figure about an axis may thus be defined as:—*The sum of the products of the constituent particles of area and the squares of their respective distances from an axis.*

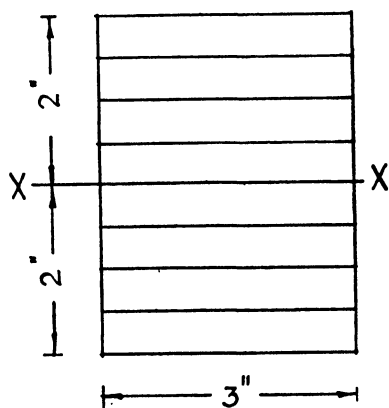


FIG. 244.—Moment of Inertia by Strip Method.

In statics the moment of inertia required is generally that about an axis passing through the centroid of the figure. Its value for any case may be found by higher mathematics, but other methods are available.

### MOMENT OF INERTIA BY STRIPS.

We may obtain an approximate value of  $I$  by considering the figure to be composed of thin strips parallel to the axis; the more strips considered the nearer does the result approach the exact value. As an example let us calculate the moment of inertia of

Fig. 244 about axis  $X-X$  passing through its centroid and parallel to the shorter side. Each portion of area is assumed to act at its centroid.

1. Consider merely the two halves of the figure.

$$\begin{aligned} \text{Then } I_{xx} &= 2 [(3\text{-in.} \times 2\text{-in.}) \times 1\text{-in.}^2] \\ &= 2 \times 6 = \underline{12\text{-in.}^4} \end{aligned}$$

2. Consider the figure divided into 4 strips.

$$\begin{aligned}\text{Then } I_{xx} &= 2[(3\text{-in.} \times 1\text{-in.}) \times 1\cdot5\text{-in.}^2] \\ &\quad + 2[(3\text{-in.} \times 1\text{-in.}) \times \cdot5\text{-in.}^2] \\ &= 2(3 \times 2\cdot25) + 2(3 \times \cdot25) \\ &= 13\cdot5 + 1\cdot5 = \underline{15\text{-in.}^4}\end{aligned}$$

3. Consider the figure dividend into 8 strips.

$$\begin{aligned}\text{Then } I_{xx} &= 2[(3\text{-in.} \times \cdot5\text{-in.}) \times 1\cdot75\text{-in.}^2] \\ &\quad + 2[(3\text{-in.} \times \cdot5\text{-in.}) \times 1\cdot25\text{-in.}^2] \\ &\quad + 2[(3\text{-in.} \times \cdot5\text{-in.}) \times \cdot75\text{-in.}^2] \\ &\quad + 2[(3\text{-in.} \times \cdot5\text{-in.}) \times \cdot25\text{-in.}^2] \\ &= 9\cdot1875 + 4\cdot7025 + 1\cdot6825 + \cdot1875 \\ &= \underline{15\cdot76\text{-in.}^4}\end{aligned}$$

This last result is nearer to the true value than the previous result. If we were to take 16 strips we should get nearer still, and so on, but the margin of error would narrow appreciably. The correct value is  $16\text{-in.}^4$ , and we will verify this when we have elucidated the formula.

**EQUIMOMENTAL SYSTEMS.**—*If a system of points be found so that, when an area is divided and assumed concentrated at those points, the sum of the moments of the areas about an axis is equal to that of the whole area about the axis, then the points form an equimomental system.*

The simplest figure to demonstrate this is the triangle, and in this case the equimomental system comprises 3 points, each at the mid-point of a side of the triangle. (See A, B and C, in Fig. 245.) Let the area of the triangle be A, then if we take  $\frac{A}{3}$  as acting at each of the points, the first moment, second moment, etc. of these quantities about any axis are equal to the first moment, second moment, etc. of the whole triangle about the same axis.

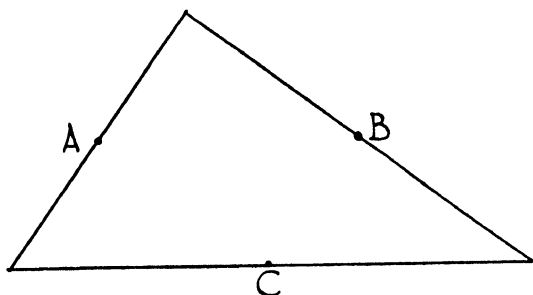


FIG. 245.—Equimomental System for Triangle.

Now the triangle is not a common structural section, but any straight-sided figure may be divided into triangles and their equimomental systems combined to give a system for the whole figure. Let us take the case of the rectangle. Let the rectangle be divided into two triangles as shown

and let the area of the *rectangle* be  $A$  or  $bd$ , where  $b$  = breadth and  $d$  = depth. Then this area will be divided amongst five points as indicated. Note that the central point is common to both triangles and therefore "takes" twice as much area as the others.

Let us now find the first moment of the rectangle about an axis coinciding with the base. Taking moments about this axis we have :—

$$\begin{aligned} & \left( \frac{bd}{6} \times d \right) + \left( \frac{bd}{6} + \frac{bd}{6} + \frac{bd}{3} \times \frac{d}{2} \right) + \left( \frac{bd}{6} \times 0 \right) \\ &= \frac{bd^2}{6} + \frac{bd^2}{3} + 0 = \frac{bd^2}{2}. \end{aligned}$$

Checking this by assuming the area of the rectangle to act at its centroid we get :—

$$\text{First moment about axis} = bd \times \frac{d}{2} = \frac{bd^2}{2}.$$

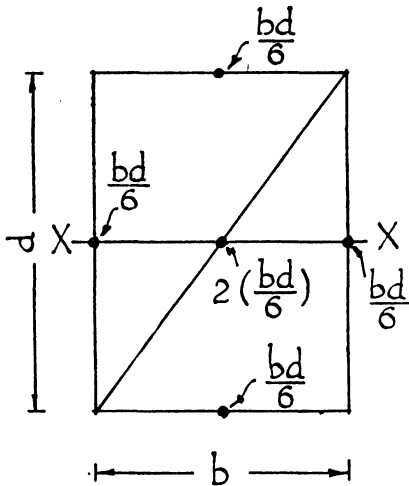


FIG. 246.—Equimomental System for Rectangle.

Now  $\frac{d}{2}$  is the mean centroid distance or leverage of all the particles of area, and this is the simpler method of finding the first moment. But when considering the second moment ( $I$ ) the leverages of all the particles are taken to the second power, and a little reflection will show that we cannot take the second moment of the figure to be  $bd \times \left( \frac{d}{2} \right)^2$ . This would be incorrect.

Having obtained the equimomental system for the rectangle (Fig. 246) let us find the second moment about axis  $X-X$ .

$$\begin{aligned} I_{xx} &= 2 \left[ \frac{bd}{6} \times \left( \frac{d}{2} \right)^2 \right] + \left( \frac{bd}{6} + \frac{bd}{6} + \frac{bd}{3} \times 0^2 \right) \\ &= 2 \left( \frac{bd^3}{24} \right) + 0 = \frac{bd^3}{12}. \end{aligned}$$

(Note that the three quantities which lie on the axis have no leverage and therefore no moment.)

Applying this formula to the rectangle, Fig. 244, we get :—

$$I_{xx} = \frac{bd^3}{12} = \frac{3\text{-in.} \times 4\text{-in.} \times 4\text{-in.} \times 4\text{-in.}}{12}$$

= 16-in.<sup>4</sup>. (Compare with the approximate result obtained on page 274.)

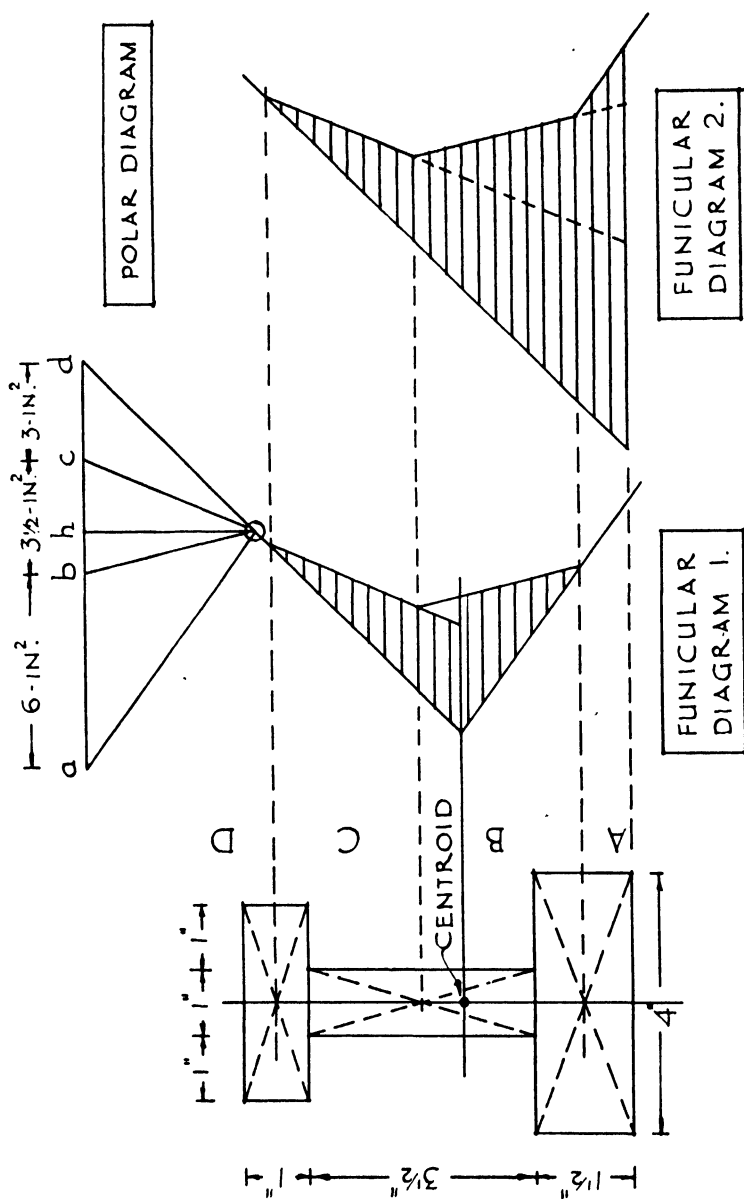


Fig. 247.—Moment of Inertia—Graphical Solution.

**MOMENT OF INERTIA GRAPHICALLY.**—To find the moment of inertia of Fig. 247. The figure is symmetrical only about one axis. If  $I$  is required about an axis passing through its centroid it is necessary first to locate this. This is done as previously shown. Now produce the funicular lines to meet the axis produced. The area of the shaded portion of the funicular diagram multiplied by twice the polar distance  $Oh$  is the moment of inertia of the figure about  $X-X$ . The second funicular diagram shown, multiplied by twice  $Oh$  gives  $I$  about an axis coinciding with the base of the figure.

**PRINCIPAL AXES OF INERTIA.**—The moment of inertia of most figures about an axis passing through the centroid has a maximum value about a certain definite axis, and a minimum value about an axis at right-angles to this. These two axes are called the *principal axes of inertia*, and for structural sections they are axes  $X-X$  and  $Y-Y$  shown in Fig. 248.

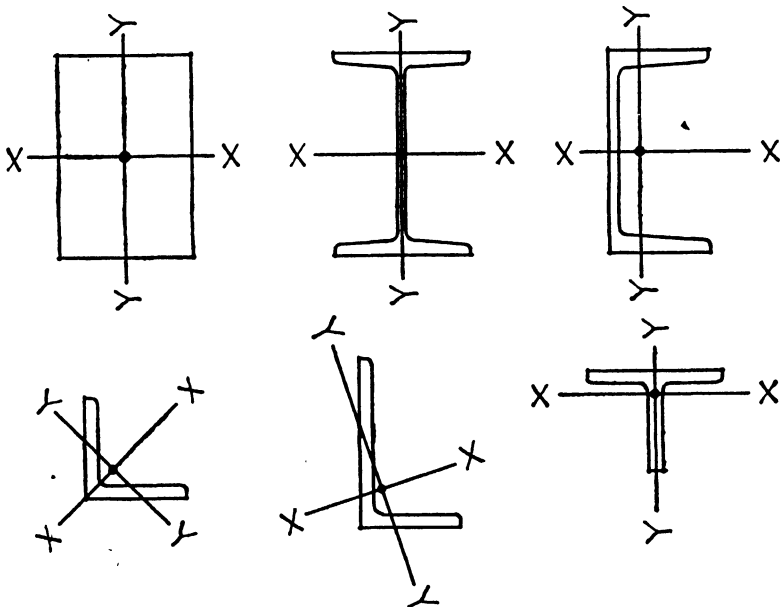


FIG. 248.—Principal Axes of Common Structural Shapes.

For a circle or hollow circle there is clearly one value only. Now the sum of the moments of inertia about any pair of axes at right-angles to each other is constant. The sum of the focal distances of an ellipse is also constant, and we can thus draw an ellipse with the centroid as its centre



and its minor and major axes along axes  $X-X$  and  $Y-Y$  respectively. Such an ellipse is known as the *Momental Ellipse*, and from it we may

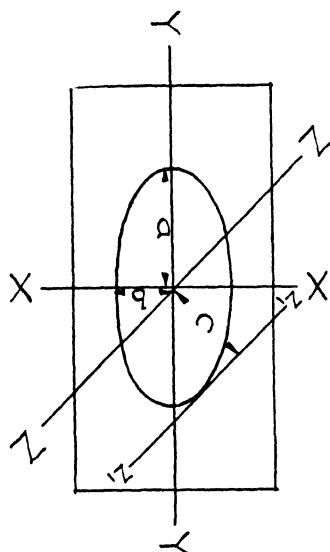


FIG. 249.—Momental Ellipse.

determine the moment of inertia of the figure about any central axis besides  $X-X$  and  $Y-Y$ . To set up the ellipse take  $I_{xx}$  in in. <sup>4</sup>, divide by the area of the figure (sq. in.) and take the square root. This gives us a linear distance (in.) which is the semi-major axis ( $a$  in Fig. 249) of the ellipse. Obtain distance  $b$  in a similar manner from  $I_{yy}$  and draw the ellipse. Now to obtain  $I_{zz}$  draw a line  $z_1-z_1$  parallel to axis  $Z-Z$  and tangential to the ellipse, measure the perpendicular distance  $c$ , square it and multiply by the area of the figure. The distances  $a$ ,  $b$ , and  $c$  are each termed the *radius of gyration* of the figure about axis  $X-X$ ,  $Y-Y$ , and  $Z-Z$  respectively. This term is explained more fully in the next section of this chapter.

**THE PRINCIPLE OF PARALLEL AXES.**—It is often required to determine the moment of inertia of a figure about an axis outside the figure but parallel to one of its principal axes, say axis  $Z-Z$  in Fig. 250.

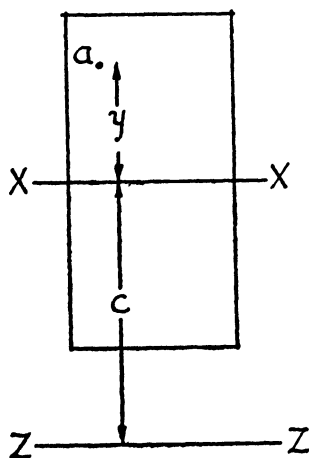


FIG. 250.—Moment of Inertia of Figure about Axis not passing through its Centroid.

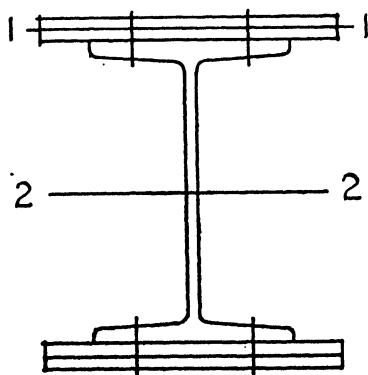
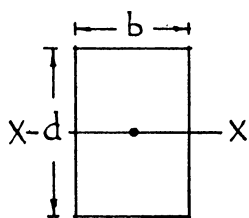
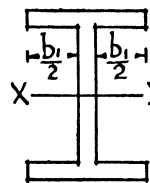
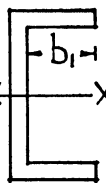
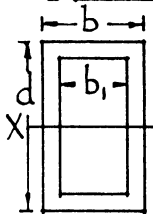


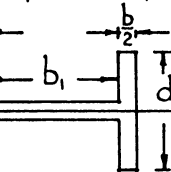
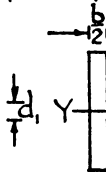
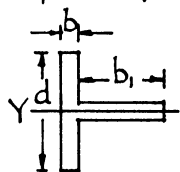
FIG. 251.—Moment of Inertia of Steel Compound Section.



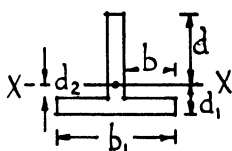
$$I_{xx} = \frac{bd^3}{12}$$



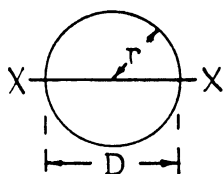
$$I_{xx} = \frac{bd^3 - b_1d_1^3}{12}$$



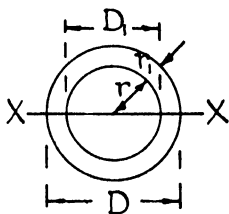
$$I_{yy} = \frac{bd^3 + b_1d_1^3}{12}$$



$$I_{xx} = \frac{bd^3 + b_1d_1^3 - (b_1 - b)d_2^3}{3}$$



$$I_{xx} = \frac{\pi D^4}{64} = .7854r^4$$



$$I_{xx} = \frac{\pi(D^4 - D_1^4)}{64} = .7854(r^4 - r_1^4)$$

TABLE 13

$$\begin{aligned}
 \text{Now, } I_{zz} &= a \times (y + c)^2 + a_1 \times (y_1 + c)^2, \text{ etc., etc.} \\
 &= \Sigma a (y + c)^2 \\
 &= \Sigma a (y^2 + 2yc + c^2) \\
 &= \Sigma ay^2 + 2c \Sigma ay + \Sigma ac^2.
 \end{aligned}$$

$$\begin{aligned}
 \text{Substituting } I_{xx} \text{ for } \Sigma ay^2 :— \\
 &= I_{xx} + 2c \Sigma ay + \Sigma ac^2.
 \end{aligned}$$

$$\begin{aligned}
 \text{Substituting } A \text{ for } \Sigma a :— \\
 &= I_{xx} + 2c \Sigma ay + Ac^2.
 \end{aligned}$$

Now,  $\Sigma ay =$  1st moment of figure about X—X = 0.

Therefore  $2c \Sigma ay = 0$ .

Thus  $I_{zz} = I_{xx} + Ac^2$ .

( $c$  is, of course, the perpendicular distance between the axes.)

Let us apply this to a practical case. Fig. 251 shows a 14-in.  $\times$  12-in. compound steel pillar composed of a 12-in.  $\times$  8-in. standard rolled steel section and a 12-in.  $\times$  1-in. steel plate rivetted to each flange. The moment of inertia of the rolled section about its own axis X—X = 487.76-in.<sup>4</sup> (taken from table). To this we have to add the values of  $I$  for both plates about this axis. To avoid confusion we have named the axes 1—1 and 2—2.

$$\begin{aligned}
 \text{Now, } I_{11} \text{ of one plate} &= \frac{bd^3}{12} = \frac{12 \times 1 \times 1 \times 1}{12} = 1\text{-in.}^4. \\
 A \text{ of one plate} &= 12\text{-in.} \times 1\text{-in.} = 12\text{-in.}^2. \\
 c &= 6\text{-in.} + .5\text{-in.} = 6.5\text{-in.} \\
 \text{Therefore } I_{22} \text{ of one plate} &= I_{11} + Ac^2 \\
 &= 1 + (12 \times 6.5 \times 6.5) \\
 &= 508\text{-in.}^4 \\
 I_{22} \text{ of both plates} &= 508 \times 2 = 1016\text{-in.}^4 \\
 \text{Therefore } I_{11} \text{ of whole section} &= 487.76 + 1016 \\
 &= 1503.76\text{-in.}^4.
 \end{aligned}$$

(This agrees with the value tabulated in the handbook.)

### 3. RADIUS OF GYRATION.

*Definition : The radius of gyration ( $g$ ) of a figure about an axis is the distance from the axis of an area, the moment of inertia of which is the same as that of the resultant of all the particles of area comprising the figure.*

If  $A =$  the area of the figure  $= \Sigma a$

and  $g =$  the radius of gyration

$$\begin{aligned}
 \text{Then } A \times g^2 &= ay^2 + a_1y_1^2 + a_2y_2^2, \text{ etc., etc.} \\
 &= \Sigma ay^2 \\
 &= I
 \end{aligned}$$

$$\text{Therefore } g = \sqrt{\frac{I}{A}}$$

An alternative definition may thus be :—*The radius of gyration of a figure about an axis is that distance the square of which is the mean of the squares of all the distances from the axis of all the constituent particles of area.*

The radius of gyration serves the same purpose with reference to the moment of inertia as does the centroid distance with reference to the first moment. It enables the whole area of a figure to be assumed concentrated at a single point, so that we may find the moment of inertia by multiplying the whole area by the square of a single distance in lieu of an infinite number of areas multiplied by the squares of an infinite number of different distances. Its use is mainly in connection with pillars and other slender compression members which endure bending as well as direct stress.

Referring to Fig. 249 we see various radii of gyration of the rectangle set down graphically. In practice the *least* radius of gyration of a section is the most important, for a long member will always bend most readily about an axis at right-angles to this. The least radius of gyration is thus in the same direction as the least breadth of a section, but it enables us to calculate stresses more exactly than we could do by merely using the breadth.

#### 4. SECTION MODULUS—Z.

We encountered this term on page 261 when considering the moment of resistance of a beam section, and found that it represented the M.R. for unit stress, say 1 ton per sq. in. We found that the section modulus about axis X—X for the rectangle in Fig. 224 was 144-in. tons, but we arrived at this result by a lengthy process of reasoning. We will now, by expressing those results algebraically, determine the formula which will enable us to calculate the section modulus for any figure.

Referring to Fig. 252 :—

M.R. = mean unit stress  $\times$  area  $\times$  lever arm

$$= \frac{f}{2} \times \frac{bd}{2} \times \frac{2d}{3} = \frac{2 fbd^2}{12} = \frac{fbd^2}{6}$$

or M.R. = max. stress  $\times$  stress area  $\times$  lever arm

$$= f \times \frac{bd}{4} \times \frac{2d}{3} = \frac{2 fbd^2}{12} = \frac{fbd^2}{6}$$

$$\text{Therefore for unit stress M.R.} = \frac{1 \cdot bd^2}{6} = \frac{bd^2}{6}$$

$$\text{and Z (section modulus)} = \frac{bd^2}{6}$$

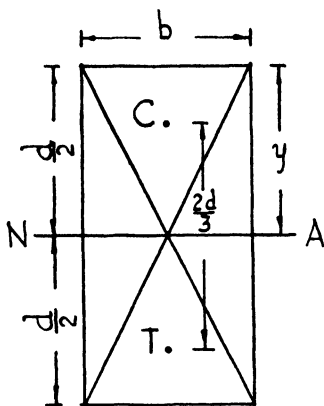


FIG. 252.—Section Modulus of Rectangle.

This is the value of  $Z$  for any rectangle about the two principal axes  $X-X$  and  $Y-Y$ .

The section modulus for a rectangle 12-in.  $\times$  6-in. about axis  $X-X$  is thus:—

$$Z = \frac{bd^2}{6} = \frac{6 \times 12 \times 12}{6} = 144\text{-in.}^3$$

$$\text{About axis } Y-Y \text{ its } Z = \frac{bd^2}{6}$$

$$= \frac{12 \times 6 \times 6}{6} = \underline{72\text{-in.}^3}$$

(Note that  $Z$  is in linear units to the third power, in this case inches<sup>3</sup>—do not think of  $Z$  as a cubic measurement.)

Now, where  $\frac{d}{2}$  is the distance from the neutral axis to the extreme outer

layer or strip of area,  $\frac{bd^2}{6} \times \frac{d}{2} = \frac{bd^3}{12}$  and this will be recognised as the value of the moment of inertia of the rectangle. The distance from the neutral axis to the extreme edge of the section (where stress is maximum)

is denoted by the letter  $y$ ; it is only  $\frac{\text{depth}}{2}$  in those cases where the N.A.

is at half depth. From this we get the general statement:— $Z = \frac{I}{y}$

For rolled steel sections the values of  $I$ ,  $Z$ ,  $g$ , etc., are tabulated in the lists or handbooks of standard sections and these values are accepted and used in calculations. In view of the complicated nature of these sections it would be extremely difficult to calculate such values for oneself.

We are now able to decide upon a section of beam for any simple case and to show the application of the formula we will work an example.

**EXAMPLE.**—A beam, supported at the ends, is to carry a central point load of 3 tons. The span is 16-ft. Select a suitable rolled-steel section, limiting the bending stress to 8 tons per sq. in. Neglect the weight of the beam.

$$\text{B.M. max.} = \frac{Wl}{4} = \frac{3 \text{ tons} \times 16\text{-ft.} \times 12}{4} = 144\text{-in. tons.}$$

We therefore require a M.R. of 144-in. tons.

$$\text{Now, } Z = \frac{\text{M.R.}}{f} = \frac{144\text{-in. tons}}{8 \text{ tons sq. in.}} = \underline{18\text{-in. units.}}$$

From the list of standard sections we find that the 9-in.  $\times$  4-in. section at 21-lb. per ft. has a  $Z$  of 18. This section would thus be suitable, and if used would be subjected to maximum compression and tension of exactly 8 tons per sq. in.

**EXAMPLE.**—For the same conditions design a rectangular wood section—stress not to exceed  $\frac{1}{2}$ -ton per sq. in.

$$\text{B.M.} = \text{M.R.} = 144\text{-in. tons as before.}$$

$$\text{Therefore } Z \text{ required} = \frac{\text{M.R.}}{f} = \frac{144}{.5} = \underline{288\text{-in. units.}}$$

$$Z \text{ for rectangle} = \frac{bd^3}{6} = 288$$

$$\text{Assume } b = 9\text{-in.}$$

$$\text{Then } d^3 = \frac{288 \times 6}{9} = 192$$

$$\text{and } d = \sqrt[3]{192} = 13.86, \text{ say } 14\text{-in.}$$

The section would thus be 14-in.  $\times$  9-in.

Both these sections would be free from excessive sag or deflection, but the method of designing to resist bending does not ensure this. The deeper the section the less is the liability to excessive bending. For a given section modulus therefore the section chosen should be the deepest consistent with lateral rigidity. The following rectangles each have a section modulus  $X-X$  of 144 :—14  $\times$  4.4, 13  $\times$  5.11, 12  $\times$  6, 11  $\times$  7.14, 10  $\times$  8.64, but bearing in mind lateral rigidity the 12  $\times$  6 is clearly the most suitable, unless the beam can be stiffened by strutting it to some other member, when the earlier sections would be not only stiffer but more economical as to cross section.

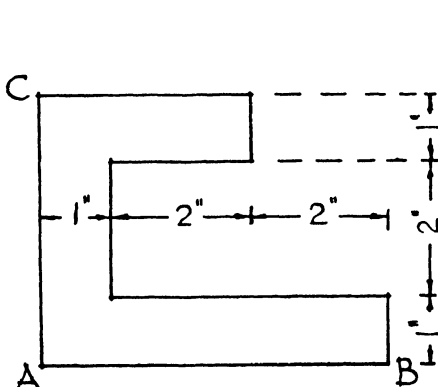


FIG. 253. Figure for Ex. 1, p. 284.

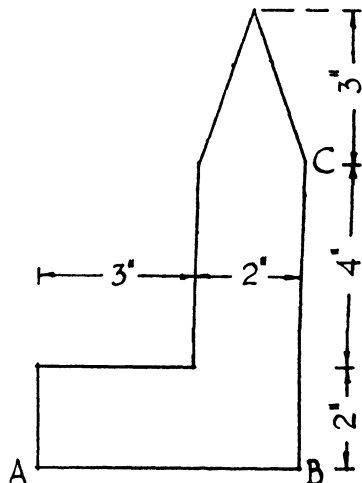


FIG. 254.—Figure for Ex. 2, p. 284.

**Exercises.**

- Find by calculation the position of the centroid (Fig. 253) with reference to lines AB and AC. (R.I.B.A. Inter.)  
(Ans. 1.7-in. from A.B. 1.8-in. from AC.)
- Find the position of the centroid shown in Fig. 254. (R.I.B.A. Inter.)  
(Ans. 3-in. from AB. 1.71-in. from AC.)
- Determine graphically the position of the centroid of the figure shown in Fig. 255. Indicate its position in reference to AB and BC.  
(Ans. 2.21-in. from both.)
- Find by calculation the moment of inertia of a 10-in.  $\times$  8-in. rectangle about its axis X—X.  
(a) By considering 10 strips.  
(b) By considering 20 strips.  
(c) By formula.  
(Ans. 660. 665. 666.6.)
- Find the moment of inertia of a 6-in. deep  $\times$  4-in. wide rectangle about an axis coincident with its base.  
(Ans. 288-in.<sup>4</sup>)
- Find the radius of gyration about its base of a triangle of altitude 8-in.  
(Ans. 3.26-in.)
- A beam 20-ft. span carries point loads of 2 tons, 4 tons, 2 tons and 4 tons at distances from the left support of 2-ft., 7-ft., 13-ft., and 17-ft. respectively. Find the maximum bending moment and state where it occurs. Assuming a safe stress of  $7\frac{1}{2}$  tons per sq. in. find the required section modulus.  
(Ans. B.M. max. = 29.9-ft. tons at 7-ft. from  $R_L$ .  
 $Z$  required = 48-in.<sup>3</sup>)
- A steel cantilever is fixed to a stanchion and beam and is loaded as shown (Fig. 256.) Neglecting the weight of the cantilever,  
(a) What effect is produced on the stanchion.  
(b) If the maximum stress in the cantilever is to be 8 tons per sq. in. what section modulus is required? (R.I.B.A. Inter.)  
(Ans. (a) An upward load of 8 tons is applied to the stanchion.  
(b)  $Z = 48$ -in.<sup>3</sup>)

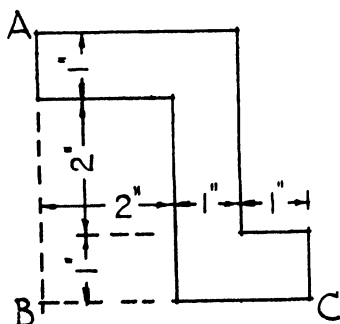


FIG. 255.—Figure for  
Ex. 3.

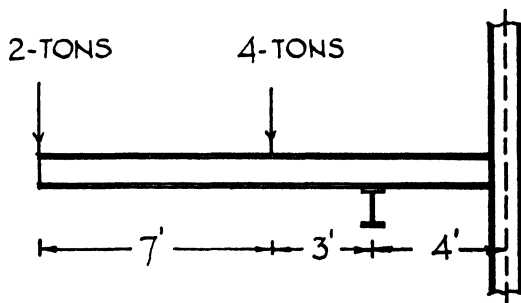


FIG. 256.—Figure for Ex. 8.

## FRAMED STRUCTURES

A framed structure is one built up of a number of members connected at their extremities so as to form an open framework. A framed tower or pylon is a framed structure, clearly in a different category to an ordinary building. Some buildings are, however, built around a skeleton framework of steel or reinforced concrete, the spaces of the frame being subsequently filled in with floors, walls, etc. But in this chapter it is with *planar* frames that we are concerned, such as roof trusses, framed girders, etc. This type of construction is usually necessary when a comparatively light construction is required to span a considerable distance, and in such cases all the members of the frame lie in a single plane, although some lateral support may be necessary under practical conditions.

It is possible in such a structure to arrange the members so that they have to withstand only direct stress—tension or compression—and this is the basis upon which such a structure is designed. Before the individual members may be designed it is required to determine the loads to be borne by them, and in this connection graphical methods are simpler than mathematical methods, being at the same time sufficiently accurate for practical purposes.

For the purpose of rendering the analysis of such a framed structure possible several assumptions have to be made in order to simplify the problem, and although they may not be adhered to completely in practice, any difference is on the side of safety. The assumptions made are :—

- (a) The members are connected by *pin joints*.
- (b) The frame is *triangulated*.
- (c) The members extend only from one joint to an adjacent joint.
- (d) The lines through the members corresponding to the centroids of their cross sections pass through the centre of the joint pin.
- (e) The external loads are applied nowhere but at joints, and their lines of action pass through the pins.

These assumptions need some explanation.

**PIN JOINTS.**—Consider Fig. 257. At A is shown a simple frame comprising wood bars with holes near the ends through which pass loosely fitting pins. In the frame at B the bars are connected by flat gusset pieces nailed or screwed down. If we apply a force to one corner of A, the frame will distort as shown by dotted lines *without the bars themselves*



being affected. If we apply a force similarly to frame B it withstands distortion within limits *but the bars are subjected to twisting and bending stresses.*

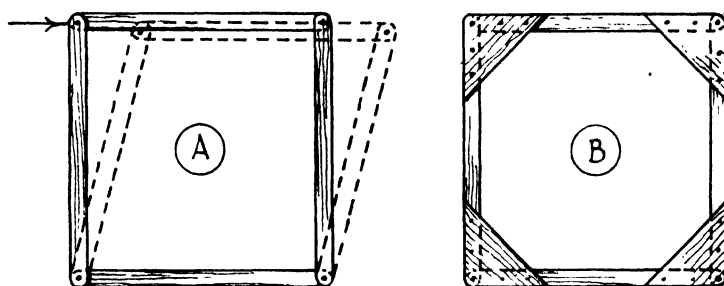


FIG. 257.—Effects of Force upon Frame.

TRIANGULATION.—Looking again at Fig 257, A, it will be seen that, under the “racking” or distortion of the frame, the diagonal distances have altered, one being reduced and the other increased. If, therefore we include in the frame a diagonal member, also pinned, we avoid the distortion. Only one diagonal is necessary and it may be either; it is seen that it would be subjected either to tension or to compression. The frame is now triangulated, and a little reflection will show that the triangular frame is the only shape that is not subject to this distortion. All framed structures must therefore be triangulated or “trussed.”

It is usually clear from inspection whether a frame is triangulated or not, but it is not so obvious whether it is a *perfect frame*. A perfect frame has the correct number of members to prevent distortion when loaded at the joints, no more and no less. To determine whether a frame is perfect or not the following rule may be applied:—*In a perfect frame the number of members = (twice number of joints) — 3.* In Fig. 258, at A, is a simple

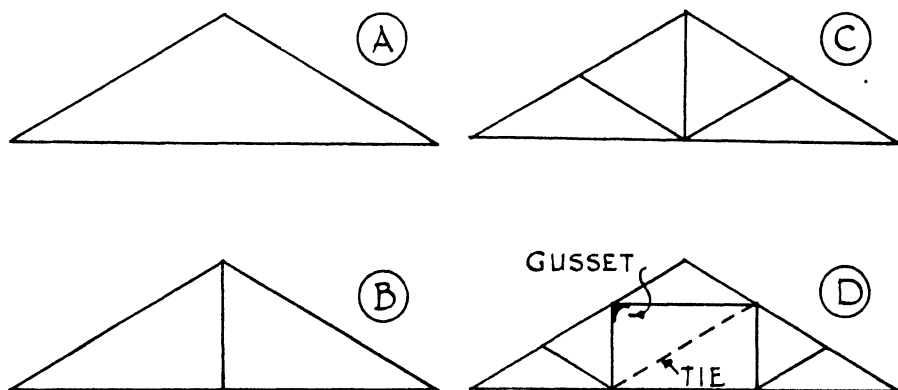
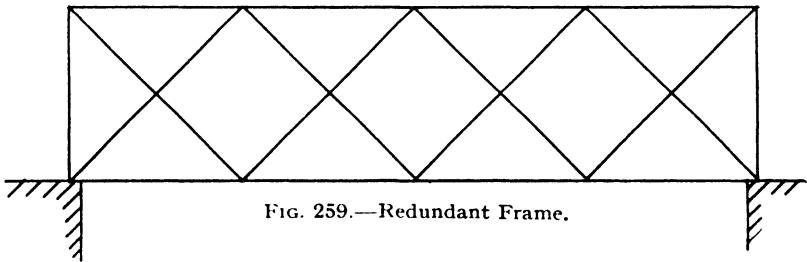


FIG. 258.—Perfect and Deficient Frames.

triangular frame. The number of members is 3 and the number of joints 3. This is therefore a perfect frame. The frame at B has 5 members and 4 joints; this is also a perfect frame. At C we have 9 members and 6 joints, also a perfect frame, but at D the frame has 14 members and 9 joints. Now  $(2 \times 9) - 3 = 15$ ; the frame thus needs one more member in order to be perfect, say the one shown dotted. This type of truss, however, is used in order to give working space in the roof and the introduction of the dotted member would upset this arrangement. Such trusses are therefore provided with gussets like the one shown, and these take the place of the missing member, but do not comply with the theoretical assumption. In order to be statically determinate (capable of being analysed graphically) the missing member must be temporarily substituted for the gusset.



Such a frame as the one at D is known as a *deficient* frame.

A *redundant* frame is one which has more members than necessary. It too is graphically indeterminate, other than by the adoption of exceptional methods. Fig. 259 is an example of a frame which we find, on applying the rule, to be redundant.

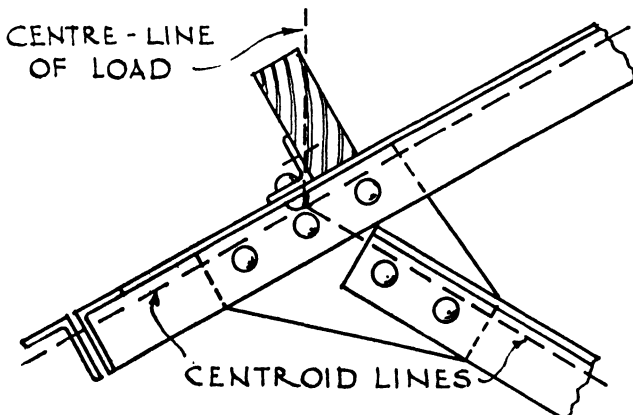


FIG. 260.—Intersection of Centroid Lines at Joint of Frame.

**EXTENT OF MEMBERS.**—In practice members often continue in a single length over more than two joints. The horizontal member in Fig. 258, C, for instance, would invariably be continuous from end to end of the truss. This practice is not in accordance with the assumption, and militates against simplicity of analysis. Its effect is to create a rigid joint at the centre, in the same way that plated and riveted joints elsewhere do not behave exactly as the pin joints assumed.

**CENTRE LINES OF MEMBERS.**—Assumptions *d* and *e* can, and always should, be observed in practice. The dotted lines in Fig. 260 show how the centroid lines of the members and the line of action of an applied load can, with no trouble, be arranged to intersect and so avoid moments.

**LOADS APPLIED AT JOINTS.**—This assumption is invariably observed. If loads were to be applied other than at the joints it is clear that bending and shearing stresses would be induced in the members, so rendering a simple treatment impossible. The members would also have to be designed to resist such stress and would be of larger and different sections to those usual. It sometimes happens that the bottom member of a roof truss is required to support loads from shafting other than at the joints, or even to support a platform or floor for storage purposes. In all such cases the frame cannot be determined by simple methods and such a member should be designed as a beam.

## STRESS DIAGRAMS.

The joints of a framed structure constitute systems of concurrent forces and may each be solved by the principle of the polygon of forces.

We will take as our first example the simple triangular frame shown in Fig. 261. Supported at the ends the reactions are 2 cwt. each, since the frame is symmetrical. For an asymmetrical frame or load system the reactions may be found by polar and funicular diagram or by calculation. It is essential that the reactions be found as a first step because they are forces acting on the frame, and in most cases we are compelled to start by solving the joint at this point.

First draw a space diagram and name the forces and the members by Bow's notation. At any joint, or nucleus of forces, we now know the direction of each force. We know the sense and magnitude of only the applied forces, but we can find the sense and magnitude of the others by reciprocal or vector diagrams, *provided that at each nucleus not more than 2 forces are not fully known.*

The problem now resolves itself into drawing a vector diagram for each separate nucleus of forces. This is done in Fig. 261, where separate space diagrams have for clearness also been drawn, so that the sense of the unknown forces may be indicated on them by arrowheads. It will

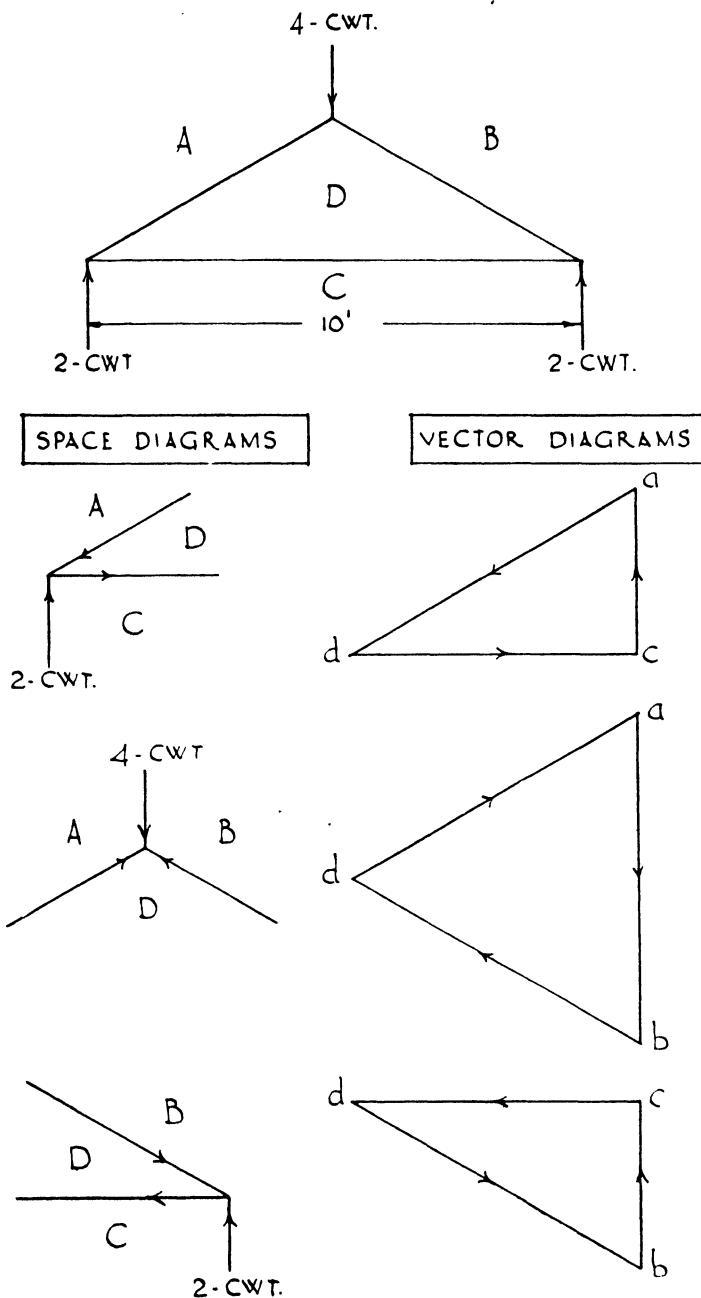


FIG. 261.—Determination of Stresses in Bars of Frame—  
Separate Vector Diagrams.

be seen, from an inspection of the three vector diagrams, that each of the vectors is common to two vector diagrams, although the sense arrowheads are reversed. We can therefore combine all into a single vector diagram provided that we forgo the inclusion of the arrowheads indicating sense. This is the usual procedure and will now be done (Fig. 262), the order of procedure being described in detail. Such a combined diagram is called a *stress diagram*. It is sometimes referred to as a *force diagram*, but the first name is preferable because the loads are forces and these are known from the commencement, and set down in the line of loads. The remainder of the diagram represents the stresses in the members, these all being unknown at the commencement. In addition the space diagram might also be called a force diagram, since the forces acting on the frame are all indicated on it.

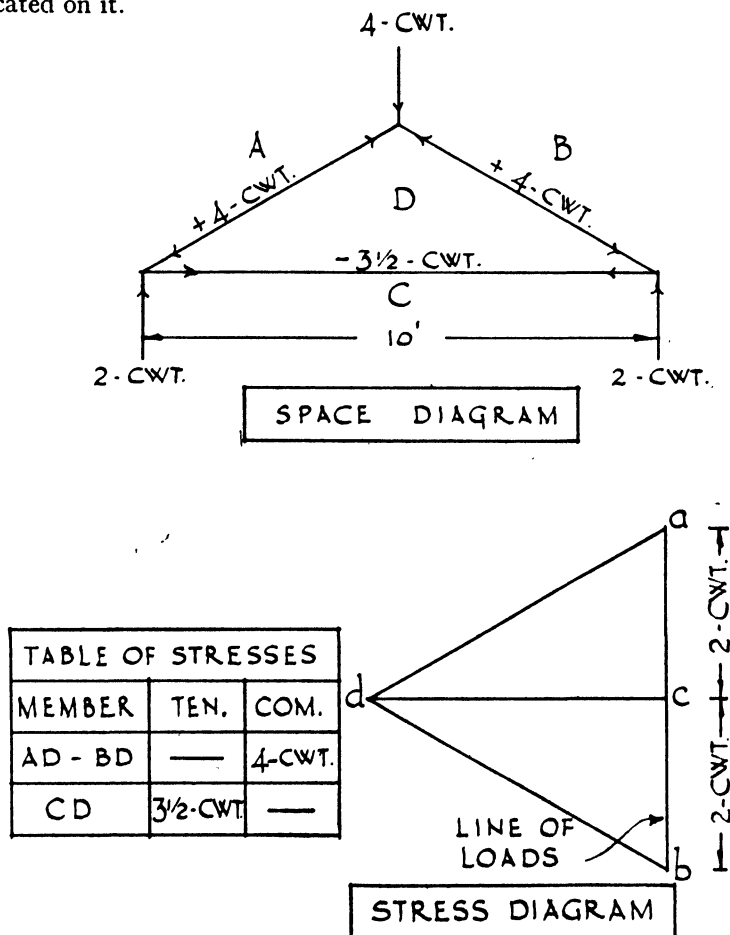


FIG. 262.—Vector Diagrams combined in Stress Diagram.

**TRIANGULAR TRUSS WITH VERTICAL LOAD.**—Draw to a suitable scale the space diagram, name the forces and members, and insert the reactions. Now to a suitable scale draw the line of loads, representing the applied forces, and then start with the left-hand nucleus CA, AD, DC. Here, the only fully known force is reaction CA. Find *ca* on the line of loads, remembering that this vector extends *upwards* from *c* to *a*; this gives the sense although the arrowhead is missing, as it would conflict with that of vector *ab*. Having dealt with force CA our next in clockwise order is AD. Vector *ad* therefore passes through point *a* on the line of loads, but whether *d* is to the left or right of *a* we do not yet know. The next force in order is DC and, as *d* is common to *ad* and *dc*, *d* must be to the *left* of *a*, since *dc* must be horizontal. *Before proceeding further* transfer the sense of *ad* and *dc* to AD and DC by inserting the arrowheads. The arrowhead to AD *pushes* towards the joint—AD is therefore in compression. The arrowhead to DC *pulls* away from the joint. DC is thus in tension.

Consider next the nucleus at the top of the frame. As we have found AD to be in compression we can insert its arrowhead at once—note that it again *pushes* towards the joint, *but not to the same joint as before*. We can now proceed to deal with the forces at this nucleus in clockwise order thus:—DA (trace *da* on the stress diagram), AB (trace *ab*) and BD (point *d* has already been fixed and all that is required now is to join *bd*). Proceed now to transfer the sense of *bd* to BD.

The final nucleus is BC, CD, DB, and since we now know the sense of DB, CD, we may put on their arrowheads without further work on the stress diagram.

All that remains is to find the magnitude of the stresses in the members by measuring (to the line of loads scale) the lengths of the various vectors. These may be indicated in a table (preferably) or in the case of a small frame such as this, the magnitudes may be lettered along each member in the space diagram. Both methods are shown in Fig. 262.

**KING POST TRUSS WITH VERTICAL LOADS.**—In this volume we are dealing only with structures subjected to vertical loads. In practice roof trusses are called upon to resist wind pressure in addition to the vertical dead loading but the more complicated treatment of this is beyond the scope of this volume.

Fig. 263 shows how the weight of the roof construction is apportioned between the roof framework. Each truss is assumed to support the shaded extent of roof, extending from the mid-lines of the bays on either side of it. If we know the equivalent weight per sq. ft. of roof surface of the various items of construction we can calculate the total weight of this area to be carried by one truss. A table of such weights is given on page 305, but assuming for the moment that the total load on the truss shown (Fig. 265) is 5,600 lb., it is split up and applied to the truss as shown in Fig. 264.

The ridge and purlins each carry one-quarter of the total load and the wall plates each one-eighth. The end trusses of a range each carry only one-half of the load taken by the remainder, but they are invariably made identical with the others for uniformity.

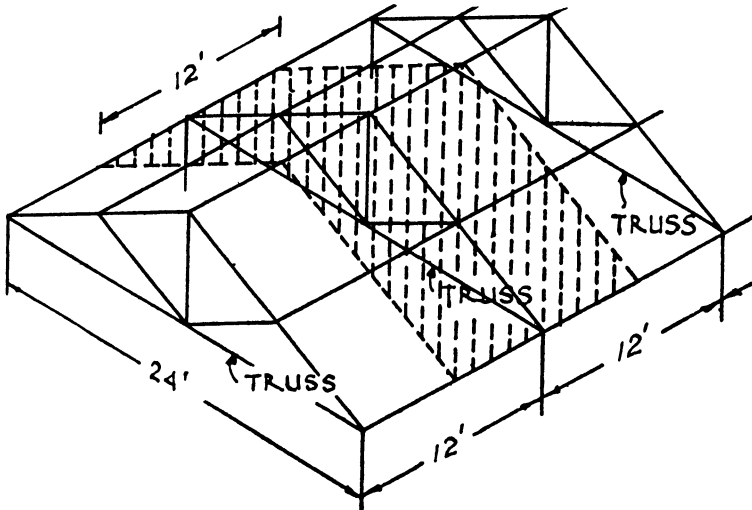


FIG. 263.—Proportion of Roof Load carried by Truss. .

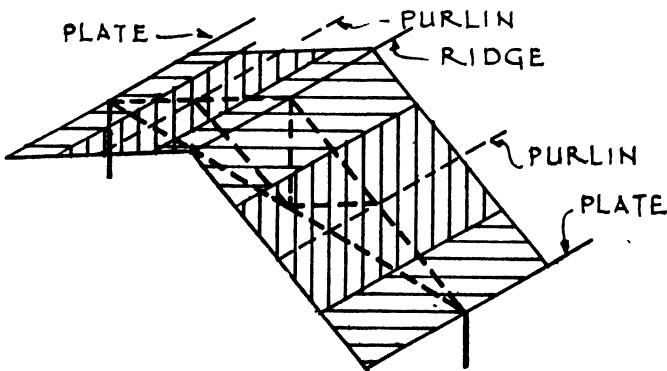


FIG. 264.—Proportion of Truss Load carried by Ridge, Plate and Purlins.

The reactions of our truss are 2,800 lb. each. Using Bow's notation name the forces and members—note that letter I is not used—this is intentional as it is easily mistaken for the figure 1 or the letter J. Now draw the line of loads to a suitable scale, say 100 lb. to 1 inch; this is where a decimal rule is convenient. Proceed with the stress diagram as described, measure the magnitudes and tabulate them as before. Note

that after working nucleus ABHG we must next take BCJH and so find HJ before we can tackle nucleus HJKLG. Note also that the loads AB and EF do not affect the stresses in the members, but it is always advisable to include them as they affect the reactions. It should also be noted that, in the stress diagram the points *h* and *l* coincide. As it happens there is no such member as HL in the frame, if there had been it would have signified no stress in the member.

**FRENCH TRUSS WITH VERTICAL LOADS.**—This type of truss is very economical because the struts HJ, LM are short, and the space K is surrounded by tension members or ties. Especially in the large sizes it may be considered as two inverted trusses held by the main tie GK.

**3-BAY TRUSS WITH VERTICAL LOADS.**—No new points arise from this example. It is given because of its frequent occurrence in practice. It should be compared with the next example.

**3-BAY FRENCH TRUSS WITH VERTICAL LOADS.**—The practical economy of this truss will be evident from inspection of the diagram (Fig. 268).

**4-BAY TRUSS WITH VERTICAL LOADS.**—The disadvantage of this truss is the great length of the struts QR and ST. It is shown in Fig. 269.

**FOUR-BAY FRENCH TRUSS WITH VERTICAL LOADS.**—This truss will be seen from Fig. 270 to be an economical form, but it has the theoretical disadvantage of being statically indeterminate. This difficulty may however be surmounted by the method shown.

Having solved joints ABL, BCNM, MNOL, we find that we cannot proceed further as at no succeeding joint are there less than three unknown forces. The simplest way is to remove members PQ, QR temporarily and substitute the new member shown dotted. The main tie SL is independent of this arrangement and it may therefore be found equally well. Having found this we may then proceed with the original arrangement of members.

**FRAMED GIRDER WITH VERTICAL LOADS.**—This example is introduced (Fig. 271) to show how loads carried by the bottom members of the frame as well as on the top are treated. In addition the line of loads is shown distorted so as to show how it is affected by these loads.

**FRAMED STRUCTURES AS BEAMS.**—All framed structures such as roof trusses act as beams, or in some cases as cantilevers, and are thus subjected to bending moments and shear forces. Their resistance to bending and shear is, however, beyond the scope of this volume.



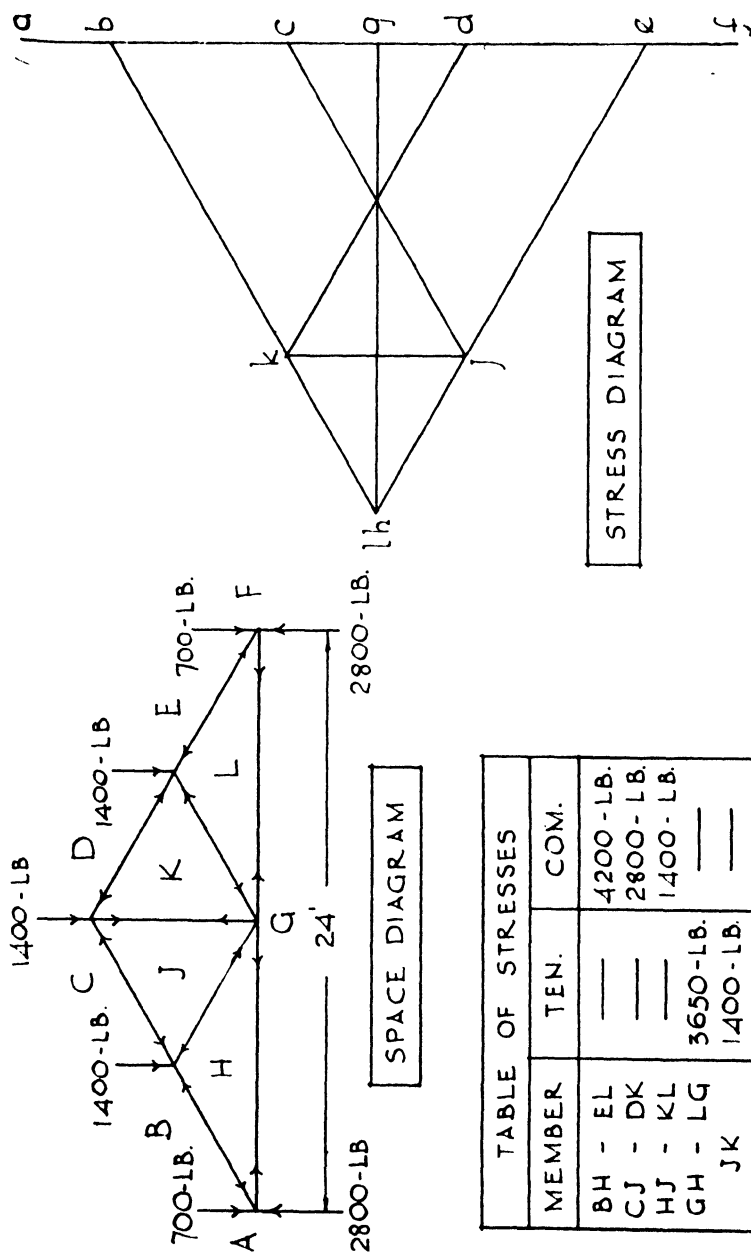


FIG. 265.—King-Post Truss with Vertical Loads—Stress Diagram.

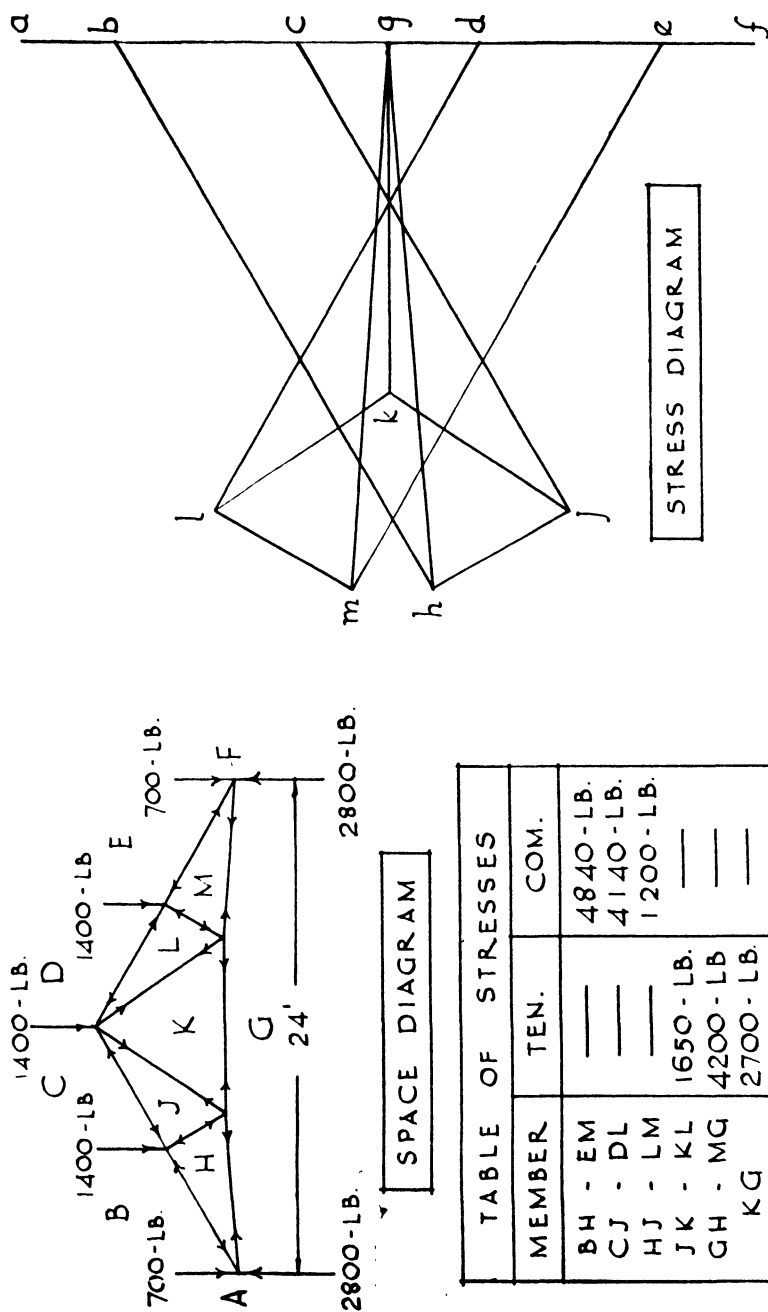


FIG. 266.—French Truss—Stress Diagram.

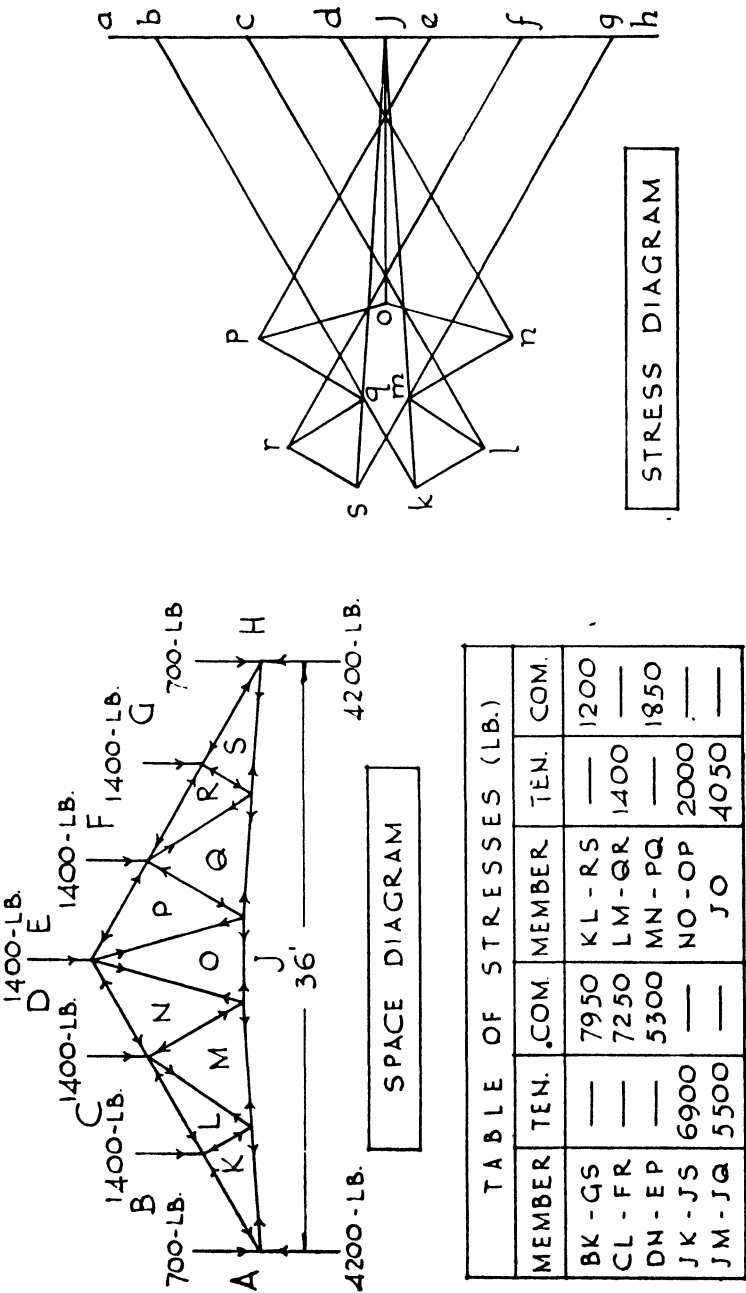


Fig. 267.—3-Bay Truss—Stress Diagram.

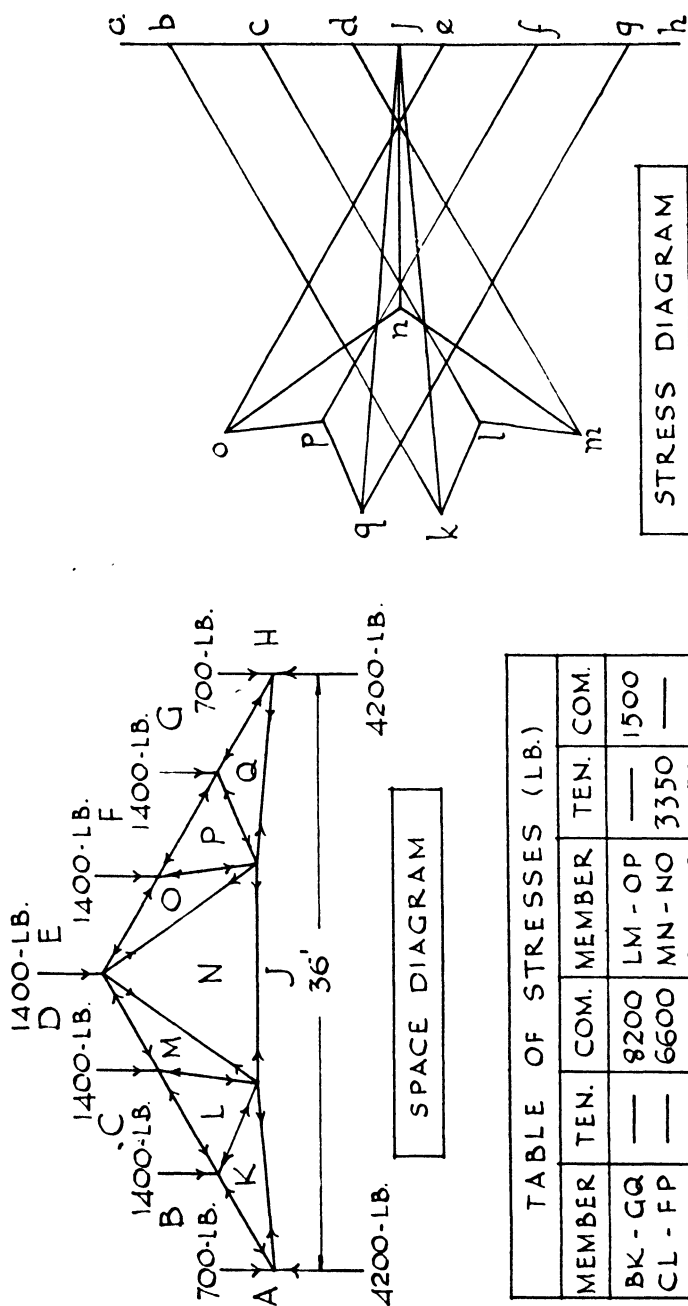


FIG. 268.—3-Bay French Truss—Stress Diagram.

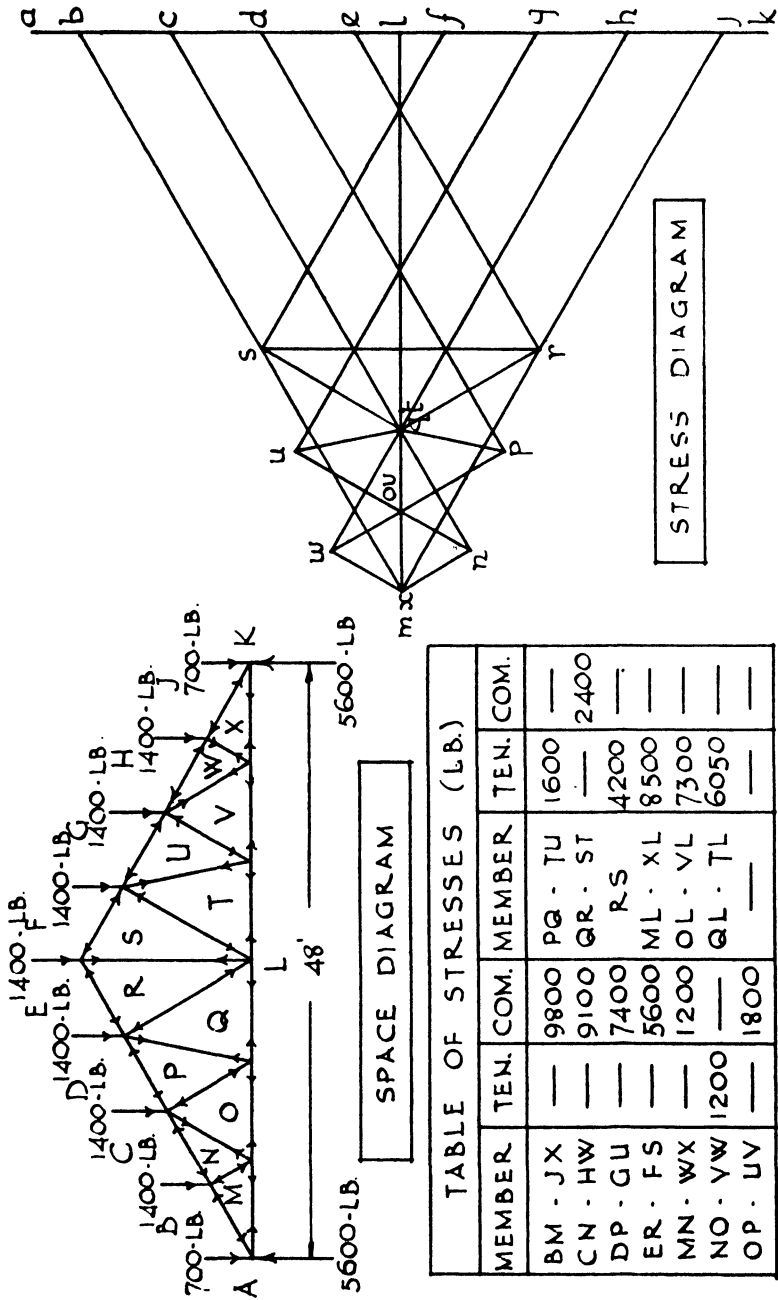
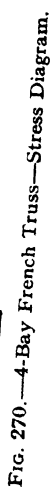


FIG. 269.—4-Bay Truss—Stress Diagram.



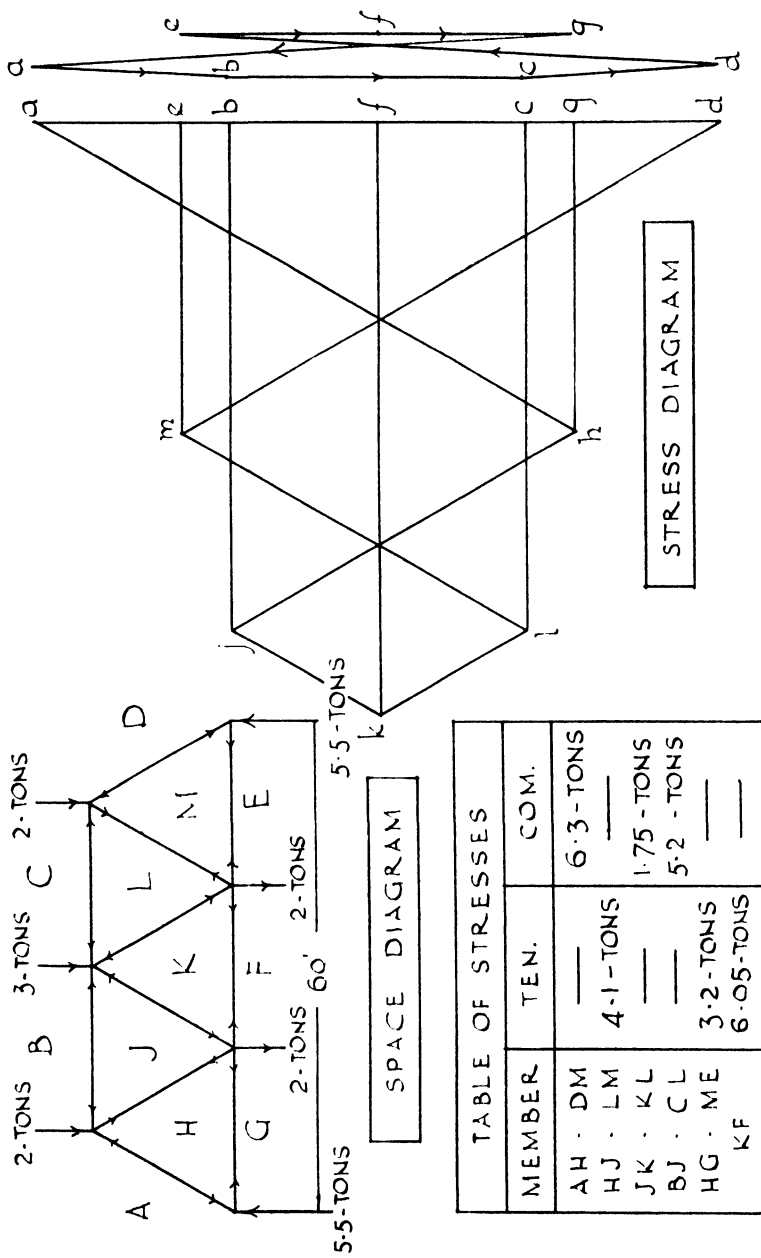


Fig. 271.—Framed Girder with Top and Bottom Loads—Stress Diagram.

### Exercises.

1. In the sketch (Fig. 272) the three rafter lengths are equal. Find the nature and amounts of the stresses in the bars of the frame. Use the following scales :—

Space diagram .. 2-ft. to 1-in.

Stress diagram .. 20 cwt. to 1-in. (R.I.B.A. Inter.)

(Ans. See Fig. 273.)

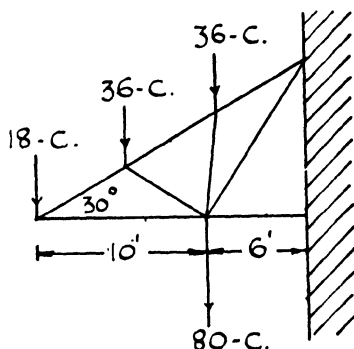


FIG. 272.—Figure for Exercise 1.

2. Fig. 274 represents a framed wall crane. Find the stresses in the members and, assuming that the upper reaction is horizontal, find its amount, also the direction and amount of the lower reaction.

(NOTE: It will have been found from these two examples that the vertical member at the wall is unstressed and could therefore be omitted without affecting the rest of the frame).

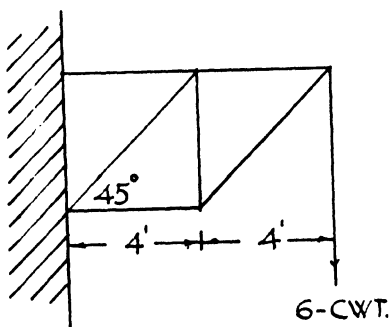


FIG. 274.—Figure for Exercise 2.

3. Fig. 276 shows a frame forming the truss of a station roof. Determine and tabulate the stresses in the members.



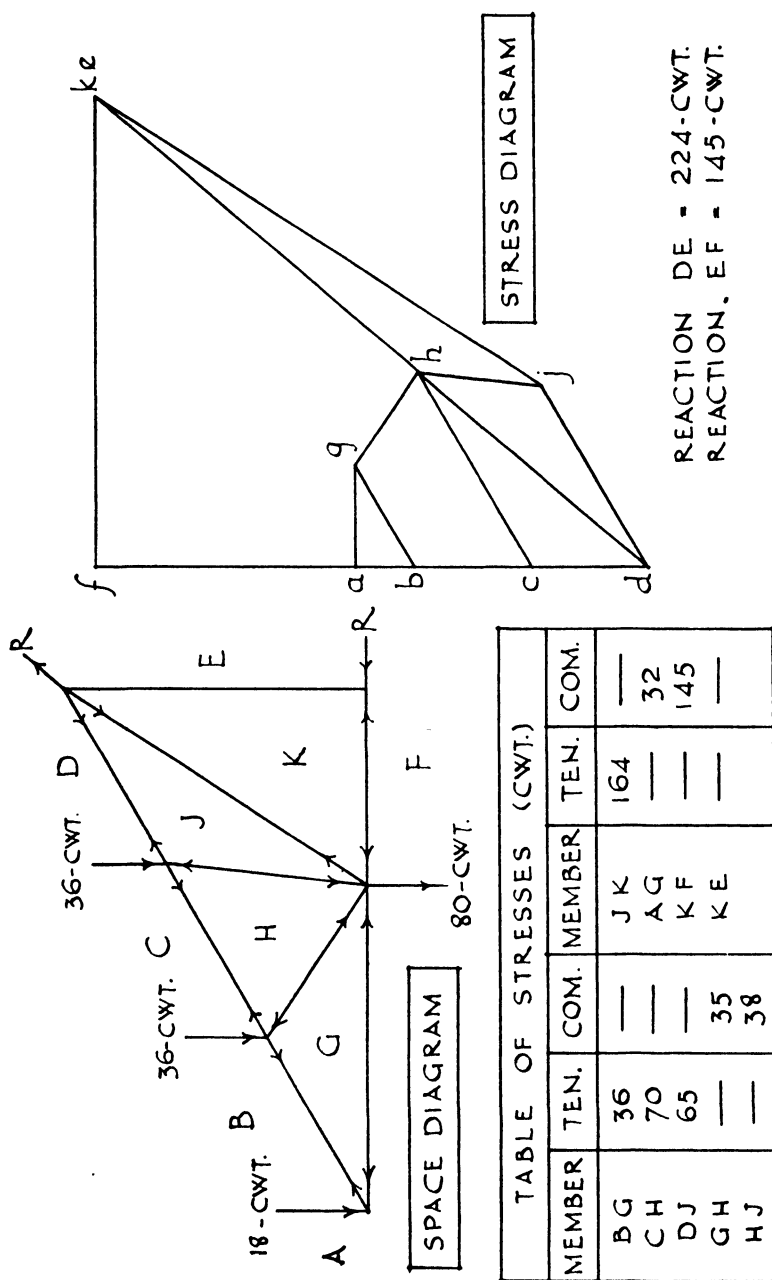


Fig. 273.—Stress Diagram for Exercise 1.

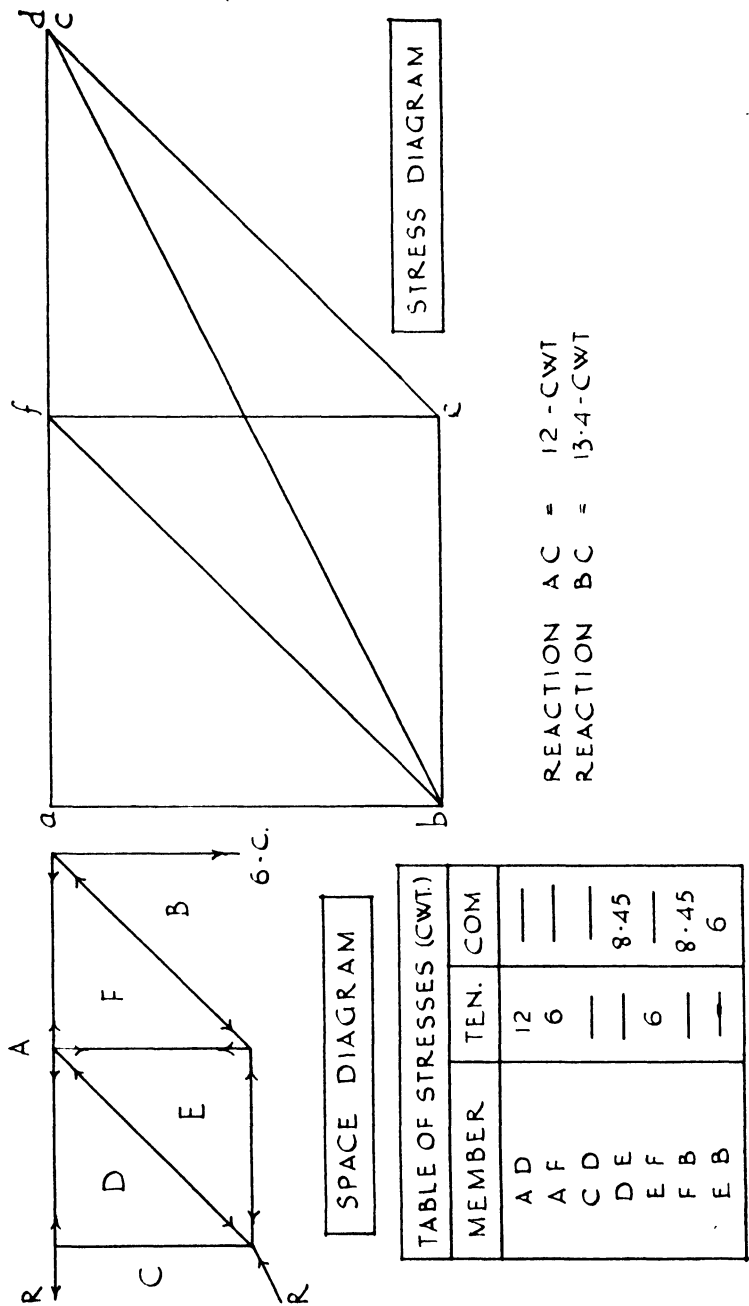


FIG. 275.—Stress Diagram for Exercise 2.

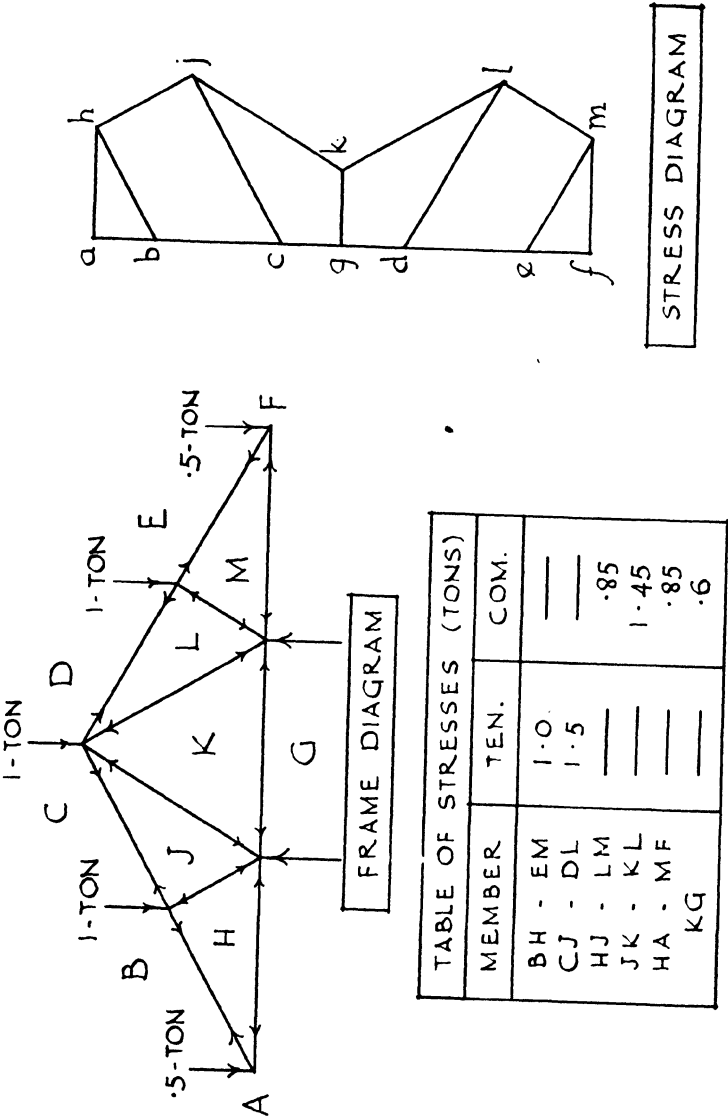


Fig. 277.—Stress Diagram for Exercise 3.

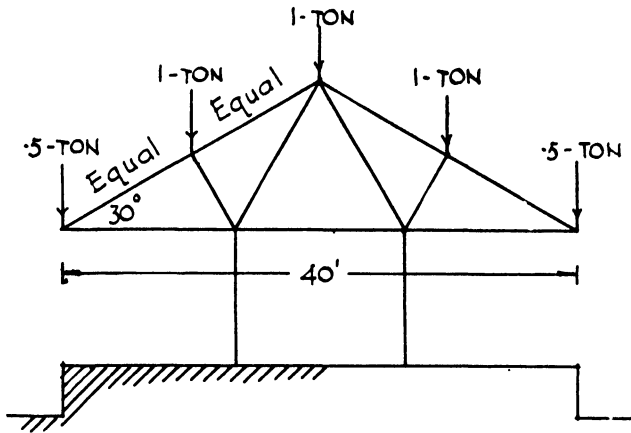


FIG. 276.—Figure for Exercise 3, page 301.

TABLE 14.

WEIGHTS OF ROOFING MATERIALS. (Lb. per sq. ft. of roof surface.)

Roof boarding—1-in. thick	..	..	3½
"    "    ¾-in.    "	..	..	2½
Slate and tile battens	..	..	1 to 1½
Common rafters..	..	..	3
Purlins—wood	..	..	4
Roofing felt	..	..	½
Slates—av. size and lap	..	..	9
Plain tiles—av. lap	..	..	17
Pan tiles	..	..	12
Rolled plate glass—¼-in.	..	..	3½
Lath and plaster ceiling	..	..	8
Ceiling joists	..	..	3 to 4

## SIMPLE MACHINES

1. *Work and Energy.*
2. *Machines.*
3. *Friction.*
4. *Efficiency.*

There are certain mechanical contrivances used in Building, notably for moving and lifting material, of the working of which it is desirable to have some knowledge. Any appliance used for changing the point of application, or the direction or magnitude of a force is called a *machine*.

## 1. WORK AND ENERGY.

We have hitherto measured forces by balancing them against known masses (scales and balance) or by noting the amount of extension they produce in a steel spring (spring balance). A force may also be measured, though not in so simple a manner, by noting its effect upon the velocity of a body, acceleration in the case of a body at rest and deceleration of a moving body. The units of force measured in this way are the *dyne* (Metric unit) and the *poundal* (British unit). One dyne is the force that produces an acceleration of 1 centimetre per second per second upon a body whose mass is 1 gram. It is a very small unit, being equivalent to a force of  $1/981$  gm. One poundal is the force that produces an acceleration of 1 foot per second per second upon a body whose mass is 1 pound. It is equivalent to  $1/32.2$  lb.

**WORK.**—*Work* is defined as *the changing of the position (or shape or size) of a body in opposition to any forces resisting such change*. It is measured by the force multiplied by the distance through which its point of application moves in the direction of the force. Work therefore equals *force  $\times$  distance*. (A moment will also be remembered as being *force  $\times$  distance*, but in this case the distance was the distance at right-angles to the direction of the force and not in the same line.)

A labourer who climbs a ladder does work in changing the position of himself and his load, the force opposing him being that of gravity. In regaining the ground he is doing no work, for although he is changing his position he has theoretically no opposition to overcome.

The units of work are the *erg* (Metric unit) and the *foot-pound* (British unit). One erg is the amount of work done when a force of one dyne acts through a distance of one centimetre. One foot-pound is *the amount of work done in overcoming a resisting force of one pound through a distance*

of one foot. Since we are concerned in this chapter with essentially practical problems we shall use British units throughout, but we must be careful not to confuse ft.-lb. of work with ft.-lb. of moment.

In measuring work, therefore, the *direction* of the resistance must be noted and also the *distance* through which it is opposed, this being in a direction opposite to that of the resistance. If a labourer picks up a 7-lb. brick from the ground, a vertical distance of 3-ft., he does work to the extent of 21-ft.-lb., opposing gravity in doing so. If he then pushes it up an inclined plank to a bricklayer he does more work in again raising it through a *vertical* distance against gravity, and also through an inclined distance against friction.

EXAMPLE.—Find the amount of work done in excavating for a pier foundation 4-ft. square and 12-ft. deep. The soil weighs 100-lb. per c. ft. before excavation.

This is equivalent to raising the whole of the soil from a horizontal plane passing through the centre of gravity, *i.e.* half the depth.

$$\begin{aligned}\text{Work done} &= \text{Weight of soil} \times \text{height raised} \\ &= (4\text{-ft.} \times 4\text{-ft.} \times 12\text{-ft.} \times 100\text{-lb.}) \times 6\text{-ft.} \\ &= 19,200 \times 6 = \underline{115,200\text{-ft.-lb.}}\end{aligned}$$

POWER.—In addition to the total amount of work done it is necessary to know the *rate* at which it is done. It is clearly more onerous to do a certain amount of work in one minute than to do the same amount of work in one hour. The *power* of a contrivance is the *rate at which it can do work*, and it is found by dividing the total amount of work by the time taken to do it. The British unit is the *horse power*, the equivalent of 33,000 ft.-lb. of work per minute. Thus if a machine overcomes a resistance of 33,000 lb. at the rate of 1 ft. per minute, or 3,300 lb. at 10 ft. per minute, or 1,000 lb. at 33 ft. per minute, etc., it is working at the rate of 1 horse-power. (H.P.)

EXAMPLE.—What is the H.P. of a winding engine which can raise uniformly at 1,000 ft. per minute a cage weighing 1,000-lb. ?

$$\text{Work done per minute} = 1,000 \times 1,000\text{-ft.-lb.}$$

$$\text{Therefore H.P.} = \frac{1,000 \times 1,000}{33,000} = \underline{30 \text{ H.P. approx.}}$$

ENERGY.—*Energy* is capacity for doing work. It is measured in the same units as work, the erg and the foot-pound. Energy may be *potential* or *actual*.

Potential energy is that possessed by a body on account of its position. A brick lying on the edge of a scaffold platform has potential energy, for if pushed over it falls to the ground and is capable of doing work in falling or on impact. A brick lying on the ground has no energy, potential or otherwise.

There are five main forms of actual energy :—Kinetic energy, Chemical energy, Radiant energy, Heat energy and Electrical energy.

Kinetic energy is energy possessed by a body as a result of its motion. The brick, in falling, has kinetic energy.

Chemical energy is that yielded or absorbed in chemical action, for instance in combustion heat and light are produced, both being forms of energy.

Radiant energy is energy radiated in the form of waves or rays travelling in straight lines in all directions at once, from some source. There are several kinds, all travelling at a speed of 186,000 miles per second, when transmitted through a vacuum. The only difference between them is one of wave-length. They include radio waves, "heat" rays, light rays, X-rays, etc.

Heat energy is the energy of vibrating molecules (see Chapter I) and is thus a special kind of kinetic energy.

Electrical energy has also been mentioned in Chapter I and is the energy of electrons moving in matter.

*Energy cannot be destroyed*; when it appears to be destroyed it is actually changed into some other form of energy. Friction produces heat, so does chemical energy. Sound energy, when absorbed, is also turned into heat—in fact instances of energy conversion are innumerable. A few are indicated in Fig. 278.

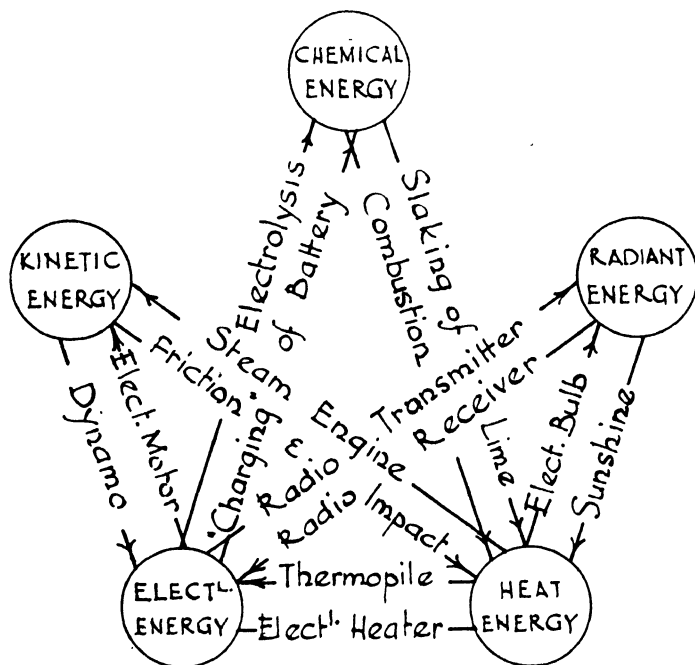


FIG. 278.—Examples of Conversion of Energy

## 2. MACHINES.

There are two fundamental types of simple machine, the lever and the inclined plane. Levers include various kinds of pulley and toothed wheels; the inclined plane includes screws and wedges. The function of these machines is to increase or reduce *forces* applied to them, usually to increase them. No machine, however, can increase the amount of *energy* applied to it, in fact some of the energy is converted into heat in overcoming friction and is so "lost."

**THE LEVER.**—The lever is a rigid bar which turns about a fixed point called the *fulcrum*. The force applied is called the *effort*, and the weight to be lifted is the *load*. Levers are of two kinds according to the relative positions of the effort, load and fulcrum. They are illustrated in Fig. 279. The principle of the lever will readily be understood from earlier study of moments, but a new point arises in the relative movement of the effort and the load. These will, however, be seen to be proportional to their leverages about the fulcrum.

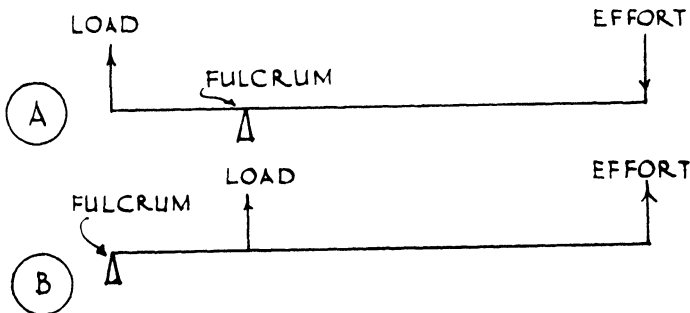


FIG. 279.—Types of Lever.

**THE WHEEL AND AXLE.**—This is identical fundamentally with the lever, and has many applications. It is shown in Fig. 280. The wheel is sometimes replaced by handles, as in the capstan or the builders' winch. It comprises two cylinders of different diameters fixed together and

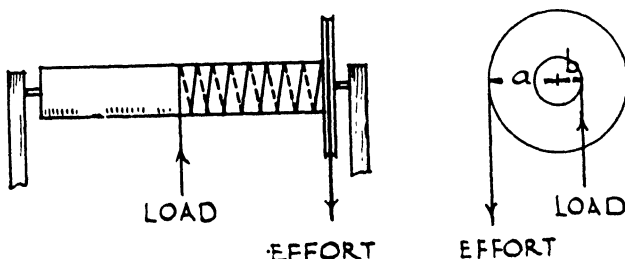


FIG. 280.—The Wheel and Axle.



working on a common axis. The leverages are  $a$  and  $b$  respectively, and for equilibrium  $\text{Effort} \times a = \text{Load} \times b$ . Therefore  $\text{Load} = \text{Effort} \times \frac{a}{b}$  (neglecting friction).

**TOOTHED WHEELS OR GEARS.**—Increased force, or conversely increased speed, may be secured by the use of toothed wheels geared together. The teeth on all wheels in the system must be of the same size and distance apart around the circumference, and it therefore follows that the number of teeth in each wheel is proportional to its circumference.

If in a system of two wheels the number of teeth are, say, 40 and 20 respectively then for each revolution of the larger wheel the smaller will make two revolutions. Occasionally as in the forge blower, etc., gears are used to produce an increase in speed with proportionately reduced force, but normally the object is an increase of force. The effort is then applied to a wheel having few teeth and these are engaged with those of a larger wheel which thus revolves at a slower rate but gives greater force. A system may of course comprise more than two wheels.

**THE COMMON PULLEY.**—A pulley is a circular disc or wheel rotating on an axle and grooved around its circumference to receive a cord or rope.

A single pulley may be used to change the direction of a force, as already explained. The force acting in the cord on either side of the pulley is identical, and the effort must therefore be equal to the load, or  $E = L$  (see Fig. 281, A).

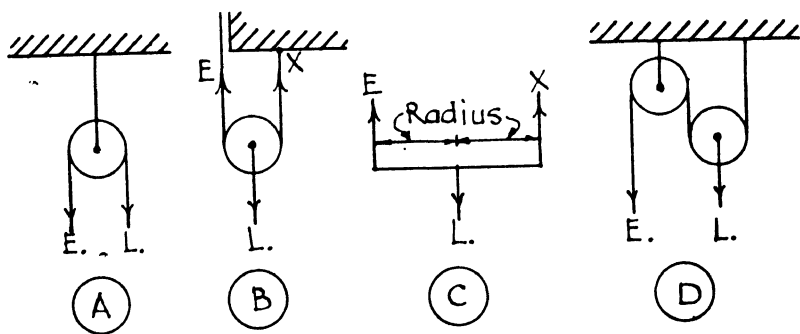


FIG. 281.—The Common Pulley.

A "movable" pulley is one whose position alters in use. In Fig. 281, B, if the cord is fixed at point X, then the effort  $E$  is equal to half the load  $L$ , or  $E = \frac{L}{2}$ . This will be clear from the diagram C which shows the forces acting upon the pulley. The effort  $E$  may be applied in a downward direction by passing the cord over a fixed pulley as at D, but the forces acting upon the movable pulley remain as before. In

practice, pulleys are mounted in blocks which may have a number of pulleys free to rotate on a single axle or pin. Fig. 282 shows a pair of blocks having a single pulley each. This is identical with that shown in Fig. 281, D, except that the fixed end of the rope is attached to the upper block, and, as before, the load is twice the effort.

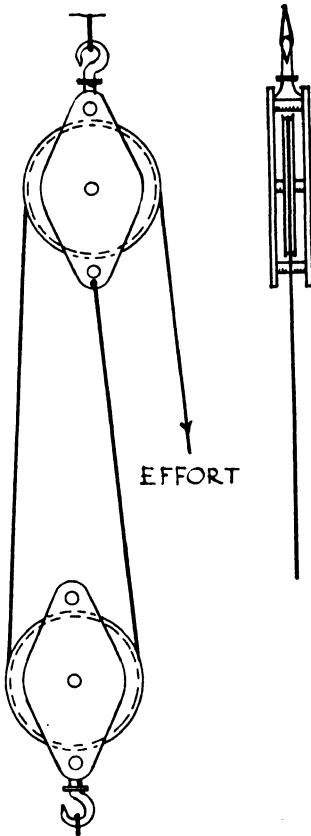


FIG. 282.—Typical Common Pulley Tackle.

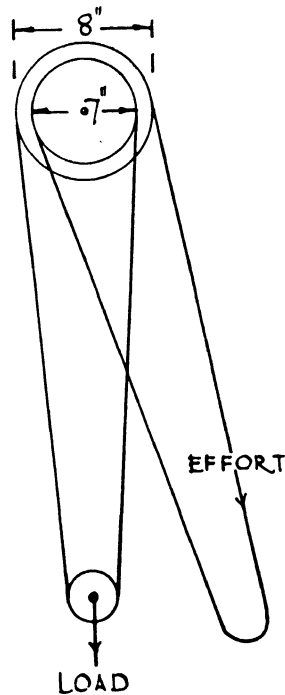


FIG. 283.—The Differential Pulley.

**THE DIFFERENTIAL PULLEY.**—This is quite different from a common pulley, and is illustrated in Fig. 283. It has a practical advantage in that the load does not fall when the effort is released. It comprises an endless chain which runs over three pulleys, the lower one of which is merely a single pulley which supports the load. The upper block has two pulleys differing slightly in diameter and made in one piece so as to rotate together on a single axle.

Suppose the diameters of the upper pulleys to be 8-in. and 7-in. respectively and an effort applied sufficient to rotate them a complete

revolution. The larger pulley has pulled *up*  $8 \times \pi$  or 25·14 in. of chain whilst the smaller one has *let down* 22 in. of chain. There is now 3·14 in. less length of chain in the loop between the pulley blocks, so that the load

has risen  $\frac{3 \cdot 14}{2} = 1 \cdot 57$ -in. whilst the effort has moved 25·14 in. Apart from friction, therefore, the load raised is  $\frac{25 \cdot 14}{1 \cdot 57} = 16$  times the effort.

It will be seen that the more nearly equal the two upper pulleys the greater is the ratio of effort to load, until if they are of identical diameter the load will not rise at all. The tensions on both sides of the pulley are not equal, as in the common pulley, and the pulley grooves are therefore toothed to prevent slipping of the chain.

**Inclined Planes.**—In Fig. 284, A we represent a body resting on a smooth horizontal plane. It is in equilibrium because the reaction  $R$  exerted by the plane is equal *and opposite* to the weight of the body  $L$ . At B the body is shown resting on a smooth plane that is inclined to the horizontal. This time the reaction exerted by the plane is neither equal *nor opposite* to it, being still at right-angles to the plane. For equilibrium, therefore, some other force is necessary. If the surfaces are rough the body may remain at rest, and in such a case the equilibrant is provided by the force of friction. If the surfaces are smooth, however, it is necessary to provide an additional applied force, say  $E$ .

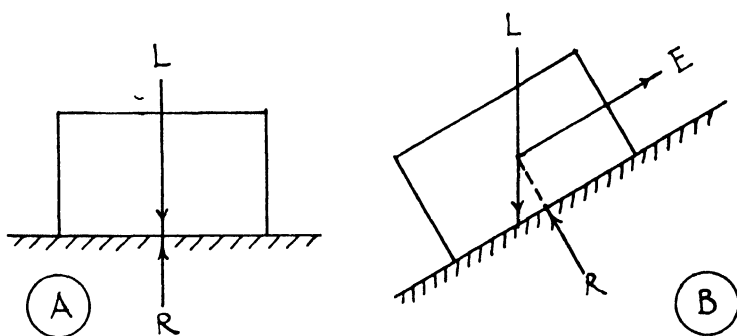


FIG. 284.—The Inclined Plane.

As the weight of the body would be known we could find  $R$  and  $E$  by the triangle of forces, as in Fig. 285, and from this it will be seen that the steeper the plane the less is  $R$  and the more is  $E$ .

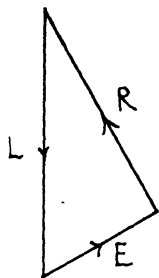


FIG. 285.  
Triangle of Forces applied  
to Inclined Plane.

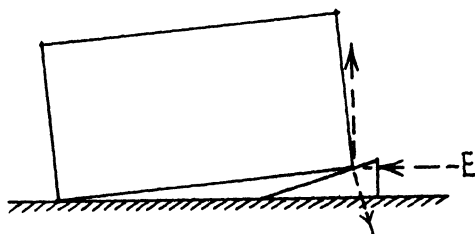


FIG. 286.—The Wedge.

**THE WEDGE.**—The wedge is a simple inclined plane which is moved by blows whilst the body (the article to be raised) remains as it were fixed. Fig. 286 shows the forces involved and from this it will be clear that the more acute the wedge the less effort will be required.

**THE SCREW.**—The screw is an inclined plane or wedge in spiral form, which in the jack is rotated about its vertical axis in order to lift a load. The pitch of the screw is the distance between the threads, so that if there are 6 threads per inch the pitch is  $\frac{1}{6}$ -in. Suppose the working length of the lever is 1-ft. 9-in. Then for a complete turn of the screw the effort moves  $\pi \times 42$ -in. = 132-in., whilst the load rises  $\frac{1}{6}$ -in. and consequently, neglecting friction, an effort of 10-lb. raises a load of  $10 \times 6 \times 132 = 7,920$ -lb. or something more than  $3\frac{1}{2}$  tons.

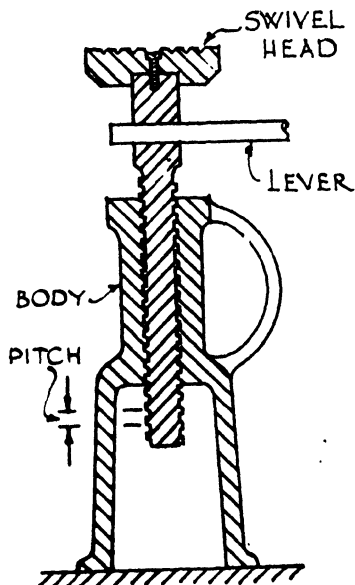


FIG. 287.—The Screw Jack.

### 3. FRICTION.

In all the machines mentioned the theoretical results are by no means realized in practice ; this is because of *friction*. Friction is the force of resistance offered when a body is made to move relative to another body whilst remaining in contact with it. We are most concerned with friction between solids, *i.e.* the resistance called into play when two solids slide upon each other. In this connection it should be noted that for given conditions the resistance, and the force necessary to overcome it, differs according to whether the force is applied in order to *start* the sliding movement or in order to *maintain* it. For instance, if we have a brick resting on a plank and we cause the brick to slide, we have to overcome the force of *static* friction. Once the brick is sliding, however, a smaller force is sufficient to keep it moving because the resistance, called *kinetic* or *sliding* friction, is less. Static friction is of more importance to us than kinetic friction, for in most cases where we have to deal with friction we are concerned with the prevention of movement, *e.g.* in mortar joints.

The amount of friction clearly depends upon the amount of the pressure between the two surfaces, and also upon their degree of smoothness. The area of the surfaces is immaterial. In the example of the brick sliding along a plank the pressure is due to the weight of the brick, and the greater this weight the more is the friction ; also the smoother the surface of the plank the less is the friction. For given materials, say the brick and the plank, the frictional resistance (which we may denote by F.R.) increases roughly in proportion to the weight or load (L). The ratio  $\frac{\text{F.R.}}{L}$ , irrespective of the magnitude of W, therefore varies according to the degree of smoothness of the two surfaces, and is used as a modulus. It is called the *coefficient of friction*, and, of course, varies in value according to the types of surface. Table 15 gives values for a few pairs of materials, not all of which are easy to determine experimentally.

TABLE 15.

COEFFICIENTS OF FRICTION.

<i>Materials</i>	<i>Coefficient</i>
Wood on wood (planed) .. ..	·45
Wood on stone .. ..	·4
Brick and unset mortar .. ..	·5 to ·75
Brickwork (set) .. ..	·7
Concrete on earth .. ..	·3 to ·5

**EXPERIMENT 129.**—To determine the coefficient of friction.

Secure to the table top a board of wood planed smooth. Lay a brick upon its face on the board and attach a sensitive spring balance to a hook or to a string tied around the brick halfway up. Now hold the ring of the balance and gently apply a uniform pull, watching the index of the balance as it travels along its scale. Note the maximum reading when the brick first starts to move. This is the *effort* (E) required just to overcome the frictional resistance, and the two may be taken to be equal. Now try, by continuing the pull on the balance, to keep the brick just moving. The minimum pull to do this will be found to be considerably less than E. By weighing the brick and working out  $\frac{\text{F.R.}}{L}$  we get the coefficient of friction for brick and wood.

If we place the brick bed downwards our result may be different according to the state of the surface.

From the statement  $\frac{\text{F.R.}}{L}$  we get  $\text{F.R.} = L \times \text{coefficient}$ .

This is used in the designing of masonry structures in ensuring no sliding due to lateral pressures, in earthworks, etc.

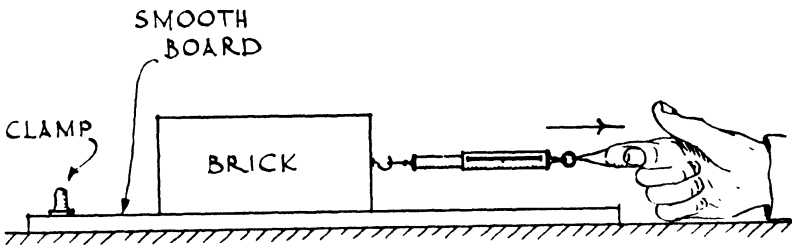


FIG. 288.—Experiment to find Coefficient of Friction.

The inclined plane may be used to find the coefficient of friction. If we rest a body on a horizontal plane and then gradually tilt the plane the body will sooner or later commence to slide. At this point the angle

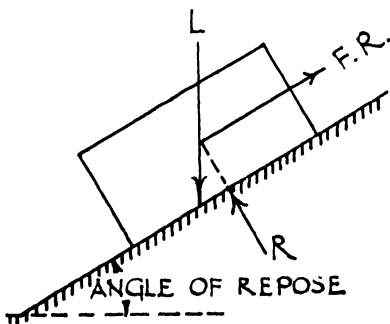


FIG. 289.—Angle of Repose.

which the plane makes with the horizontal is called the *angle of repose*, and the force of friction (F.R.) shown in Fig. 289 corresponds to the effort E shown in Fig. 284. F.R. and R may now be found from the triangle of forces,  $\frac{\text{F.R.}}{R}$  being the required coefficient of friction for the two surfaces.

**EXPERIMENT 130.**—To determine the coefficient of friction using an inclined plane.

Arrange the board so that one end may be raised by a screw, or by any other means whereby the board remains in its position of maximum tilt. Place on it the brick used in the last experiment and tilt the board slowly and uniformly. At the moment when the brick commences to move cease the tilting and then measure with a protractor the angle of repose. The weight of the brick ( $L$ ) is known,  $F.R.$  and  $R$  may thus be found, and also  $\frac{F.R.}{R}$  the coefficient of friction, which should agree with the result found in Experiment 129.

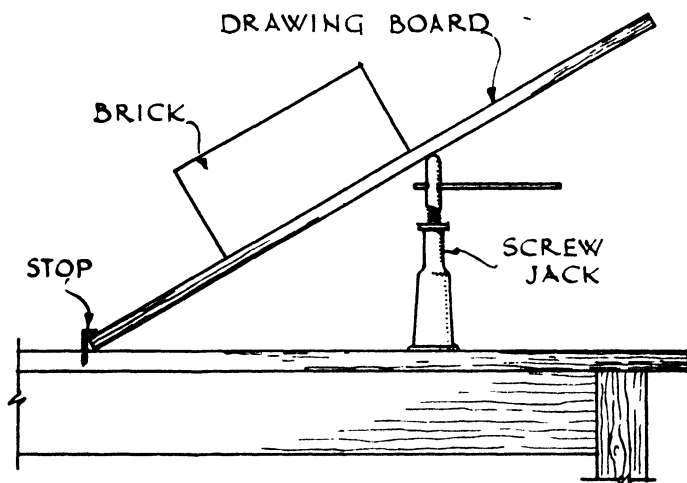


FIG. 290.—Experimental Inclined Plane.

#### 4. EFFICIENCY OF MACHINES.

If it were possible to have a perfect machine the amount of work done by it would be equal to the amount of work expended upon it, but as we have seen, some of it is transformed into heat by friction and so wasted. In the case of the lever very little is wasted but in other machines, notably the wedge and the screw, most of it is wasted. Some machines are thus more efficient than others.

**MECHANICAL ADVANTAGE.**—The *mechanical advantage* of a machine is the ratio of load to effort, or  $\frac{L}{E}$ , and it expresses the conditions of equilibrium. Neglecting friction the work done on the load is equal to that done by the effort. To take the case of the lever illustrated in Fig. 279, A, if the effort is 4-ft. from the fulcrum and the load 6-in. from it, then the effort is  $\frac{1}{3}$  of the load, and the mechanical advantage is  $\frac{4}{\frac{1}{3}} = 8$ .

Taking friction into account, however, it would be somewhat less than this.

**VELOCITY RATIO.**—In this same example, if the end of the lever to which the effort is applied moves downwards 1 ft. then the load is raised  $1\frac{1}{2}$ -in. This is clear from the statement above that the work done by both is equal; in the present case  $E \times 4\text{-ft.} = L \times .5\text{-ft.}$  Thus equilibrium will be achieved when the load has risen  $\frac{1}{8}$  of the distance through which the effort has moved downwards. This ratio of movement is called the *velocity ratio*. Neglecting friction it will be seen to be equal to the mechanical advantage, but in most machines we cannot neglect friction.

**EFFICIENCY.**—The *efficiency* of a machine is the ratio of its actual to its theoretical performance, and is equal to  $\frac{\text{mechanical advantage}}{\text{velocity ratio}}$  or  $\frac{\text{work got out of machine.}}{\text{work put into machine.}}$

The velocity ratio is calculated or is apparent from inspection of the machine; the mechanical advantage must be found as a result of actual use of the machine. In the case of the lever, if the load is 1,000-lb. and an effort of 145-lb. is found to be required to raise it, then the mechanical advantage is  $\frac{1,000}{145} = 7$  approximately. The velocity ratio is 8, therefore the efficiency of the lever is  $\frac{7}{8} = .875$  or 87.5 per cent.

**Efficiency of Various Machines.**—We will now discuss briefly the efficiency of the types of machine already mentioned.

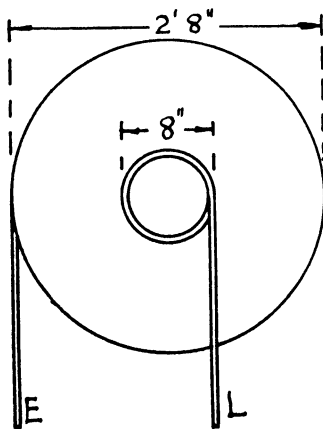


FIG. 291.—Efficiency of the Wheel and Axle.

**WHEEL AND AXLE.**—Suppose the axle is 7-in. in diameter and the wheel or handle of 1-ft. 4-in. radius. If we use a rope 1-in. thick the axle diameter will be greater by  $2 \times \frac{1}{2}$ -in., so giving an effective diameter of 8-in. The velocity ratio is clearly the ratio of the two circumferences which is equivalent to that of the two diameters or  $\frac{32\text{-in.}}{8\text{-in.}} = 4$ . To find the mechanical advantage we must measure the effort required to raise a given load—say load = 500-lb. and effort = 200-lb. The mechanical advantage is thus  $\frac{500}{200} = 2.5$ , and the efficiency =



$$\frac{\text{mechanical advantage}}{\text{velocity ratio}} = \frac{2.5}{4} = .625 \text{ or } \underline{62.5 \text{ per cent.}}$$

**THE BUILDERS' WINCH.**—The winch, as shown in Fig. 292, is a large wheel and axle in the form of a toothed wheel and winding drum, geared to a smaller wheel and axle in the form of a toothed wheel and handle. Sometimes, as in the illustration, a third in the form of two toothed wheels is interposed, and the load may be lifted direct as shown or through a system of common pulleys.

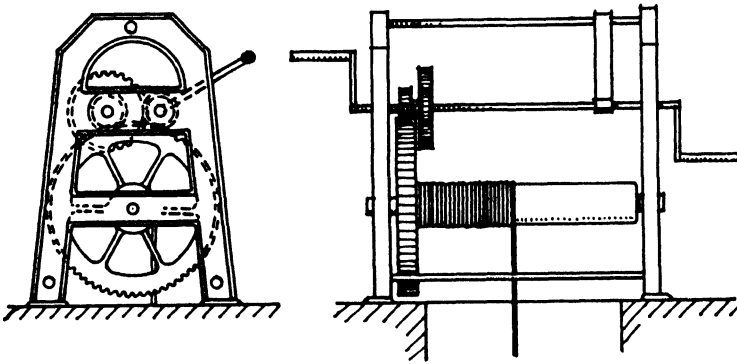


FIG. 292.—The Winch.

Suppose that the first wheel, the one driven by the handle, has 8 teeth, the intermediate pair have 8 and 24 teeth respectively and the large wheel 64 teeth. The drum is 8-in. in diameter, which with a 1-in. diameter rope gives a total diameter of 9-in. The handle is 1-ft. 9-in. long, and let us assume that we turn it one complete revolution. The load moved is 1 ton and the effort required is found to be 50-lb. The

mechanical advantage is thus  $\frac{2,240}{50} = 44.8$ . For a complete turn of the

handle the effort moves  $42 \times \pi$ -in. and the 8-tooth wheel driven by the handle turns the 24-tooth wheel with which it is meshed  $\frac{8}{24} = \frac{1}{3}$  of a revolution. On the same axle as the 24-tooth wheel and moving with it is a second 8-tooth wheel; this also turns  $\frac{1}{3}$  of a revolution and, being meshed with the 64-tooth wheel, makes this turn  $\frac{1}{3} \times \frac{8}{64} = \frac{1}{24}$  of a revolution. The winding drum therefore turns  $\frac{1}{24}$  of a revolution for a complete turn of the handle, raising the load  $\frac{1}{24} \times \pi \times 9$ -in. =  $.375\pi$ -in. in so doing. The velocity ratio is thus  $\frac{42\pi}{.375\pi} = 112$ , and the efficiency is

$$\frac{\text{mechanical advantage}}{\text{velocity ratio}} = \frac{44.8}{112} = .4 = \underline{40 \text{ per cent.}}$$

**COMMON PULLEY TACKLE.**—As the tension in the rope on both sides of a pulley is identical (neglecting friction) the mechanical advantage of pulley tackle would be equal to the number of lengths of rope between the two blocks ; thus in the tackle shown in Fig. 282 it would be 2. If the two blocks do not have the same number of pulleys the free end of the rope must be secured to the lower block : for instance a “4—3” tackle, and the mechanical advantage in this case would theoretically be 7.

Let us work out the efficiency of such a tackle. The velocity ratio is 7, since the effort must move 7 times the distance through which the load is raised. The actual mechanical advantage must be found by experiment. Assuming the load to be 140-lb. and the effort necessary to raise it 33-lb. then the mechanical advantage is  $\frac{140}{33} = 4.25$  nearly. The efficiency of the tackle is therefore  $\frac{\text{mechanical advantage}}{\text{velocity ratio}} = \frac{4.25}{7} = .607$  or 60.7 per cent.

**DIFFERENTIAL PULLEY TACKLE.**—We will take the tackle shown in Fig. 283. The velocity ratio has been found to be 16. If an effort of 138-lb. is required to raise a load of  $\frac{1}{2}$ -ton the mechanical advantage is  $\frac{1,120}{138} = 8.1$ . The efficiency of the tackle would therefore be, as before,  $\frac{\text{mechanical advantage}}{\text{velocity ratio}} = \frac{8.1}{16} = .506 = \underline{50.6 \text{ per cent.}}$

**THE SCREW JACK.**—Using the jack illustrated in Fig. 287 the load raised by an effort of 10-lb. is 1,960-lb. The mechanical advantage is then  $\frac{1,960}{10} = 196$ . As the effective length of the lever is 21-in. and the pitch of the screw  $\frac{1}{8}$ -in. the velocity ratio is  $\pi \times 42 \times \frac{6}{1} = 792$ . The efficiency is therefore  $\frac{\text{mechanical advantage}}{\text{velocity ratio}} = \frac{196}{792} = .247$  or 24.7 per cent.

Experimental work should be done with all these types of lifting apparatus, preferably the full-sized tackle, to find their respective mechanical advantage, velocity ratio and efficiency. Such work need not be detailed here.

**Exercises.**

1. A common pulley tackle consists of a 3-sheave and a 2-sheave block. If the efficiency of the tackle is 63 per cent. what load would be lifted by an effort of 50-lb. ?  
(Ans. 157.5-lb.)
2. A "2—2" common pulley tackle has a percentage efficiency of 65. Find the amount of work done in raising a load through a height of 10-ft. when the effort is 20-lb.  
(Ans. 520-ft.-lb.)
3. A builders' winch has a drum 11-in. in diameter used in conjunction with a 1-in. diameter rope. Its gear wheel has 52 teeth and the driving wheel 8 teeth. The handle has an effective length of 1-ft. 6-in. If the efficiency of the machine is 60 per cent. what effort is necessary to raise a load of 10-cwt. through a set of "3—3" common pulley tackle whose efficiency is 62 per cent. ?  
(Ans. 25.72-lb.)
4. A screw jack has a pitch of  $\frac{1}{4}$ -in. and its efficiency is 24.85 per cent. What must be the effective length of the lever used if a load of 300-lb. is to be lifted by an effort of 2-lb. ?  
(Ans. 2-ft.)
5. The pulleys in the upper block of a differential tackle are 7in. and  $6\frac{1}{4}$ -in. in diameter. Its efficiency is 50 per cent. What effort would be needed to raise a load of 6-cwt. ?  
(Ans. 48-lb.)

## SECTION III—EQUIPMENT

### CHAPTER XIX

#### HEAT

1. *Heat and Temperature.*
2. *Measurement of Temperature.*
3. *Measurement of Heat.*

Our study of Heat must be fairly comprehensive because, quite apart from the artificial heating of buildings and such problems, the effects of heat upon building materials and construction are of the greatest importance.

#### 1. HEAT AND TEMPERATURE.

In the first chapter we explained heat as the vibratory motion of atoms and molecules, always present to some degree in all kinds of matter. Heat is thus energy and not matter, for a body weighs the same whether it is hot or cold. Fig. 278 showed us that it can be converted into other kinds of energy, whilst other forms of energy can be changed into heat.

The sensation produced by heat may be mild or intense according to the degree of heat motion, or thermal state, of the body receiving the sensation. It may also be considered positive or negative ; for instance if we touch with the hand a flask of boiling water we say it is hot, whereas if we touch a piece of ice we refer to it as cold. The sensations are clearly relative to the thermal state of the hand. Cold is a "negative" term, for it is used to denote that the heat motion of a body is less than that of the body with which it is compared. *Cold is not something the reverse of heat.*

*HEAT, then, is the agency whereby certain thermal conditions are produced in a body. The term used to indicate the thermal condition (the intensity of heat motion) of the body is TEMPERATURE.*

**PROPAGATION OF HEAT.**—We may thus correctly refer to a certain *amount* or *quantity* of heat, or to heat *flowing* from one body to another, and so on, exactly as though it is something tangible and apart from the body itself. This should, however, be considered throughout as a mere convention.

Heat can be produced only by the conversion of some other form of energy, according to the *Law of the Conservation of Energy*. (This states

that energy cannot be destroyed—when energy apparently disappears it is replaced by exactly the same amount of other forms of energy.)

Kinetic energy is converted into heat by all forms of friction such as the sawing of wood, the filing of metal, the application of brakes, the contact of moving parts of machinery, etc. Impact also produces heat as in repeated blows from a hammer or pile driver. When the molecules of matter are forcibly rearranged, as in compressing air by a pump, considerable heat is produced, whilst if a steel bar is rapidly strained beyond its elastic limit the specimen becomes too hot to touch.

Chemical energy is transformed into heat in all chemical action, notably in combustion and in the slaking of quicklime.

Heat is also produced from electrical energy by the resistance offered by a material to the flow of electric currents.

The radiant energy of the sun is turned into heat when it impinges upon matter, sound waves entering an absorbent material are converted into heat, and so on.

All these are instances of heat being *propagated*; heat may also be *acquired* by a body from contact with a body having a higher temperature, the heated molecules affecting those adjacent to them.

**EFFECTS OF HEAT UPON A BODY.**—The effects of heat are dealt with in detail in subsequent chapters but the more important effects may with advantage be summarized here.

The most immediately apparent result of an increase of heat in a given body is a rise in temperature, and *vice versa*. This, however, is only true whilst the material remains in its original state—gaseous, liquid or solid.

If the application of heat to the material causes it to change its state—solid to liquid or liquid to gas—heat is absorbed without a rise of temperature whilst the change is taking place. Thus, if ice is heated its temperature does not rise until after it has been converted into water. Similarly heat is necessary to turn boiling water into steam, but again there is no rise of temperature. Conversely, when steam condenses into water and when water freezes into ice there is not a fall of temperature.

Another effect of heat is to produce a change of volume and density, expansion and decreased density by an increase of heat—contraction and increased density by a reduction of heat.

Certain other physical properties of materials become altered by heating, *e.g.* colour, hardness, elasticity, viscosity, etc.

Finally, as has already been seen, chemical action is frequently started by the application of heat.

## 2. MEASUREMENT OF TEMPERATURE.

Let us first be quite sure of the distinction between temperature and heat. A small vessel full of boiling water is just as hot as a large vessel full ; in other words the temperatures are identical, but the water in the large vessel clearly contains more heat than does that in the small one. We may thus regard temperature as a physical *state* and heat as a physical *quantity*.

The temperature of a substance is thus irrespective of its mass, and when by touch we say that the substance is hot, or very hot, or merely warm, we are referring to its temperature or degree of hotness and not to the amount of heat present.

The transfer of heat from one body to another which is in contact with it also depends solely upon a difference in temperature, not upon a difference in the quantities of heat. A very small hot body will thus lose heat to a very large body which is cooler, although the large body may contain much more heat.

The method of judging temperatures by sensation is not reliable for we have seen that our estimation differs according to the temperature of the hand, which is itself variable, and further it does not permit exact numerical measurement.

Any physical property which undergoes change with change of temperature may be utilized in the measurement of temperature—colour, hardness, electromotive force, electrical resistance, or volume, and there are in common use instruments based upon all of these.

**PYROMETERS.**—If we heat an iron bar in a furnace it changes colour gradually from a dull red to a bright red and so to orange, yellow, white and then incandescent. Such a body might therefore be used to measure these high temperatures, but would not be convenient. The same principle is however utilized in the “disappearing filament” *pyrometer* which is used to measure the temperature of furnaces, kilns, etc.

It is a small instrument with a holding handle and comprises a viewing tube in which is a fine metal filament, somewhat similar to that in a small electric light bulb. The filament is connected by wires to a battery and to a galvanometer, and by turning a screw or knob which varies the current supplied the filament glows and passes through all the stages of colour mentioned in connection with the iron bar. At any point the galvanometer needle indicates the current flowing and on a second scale is the corresponding temperature reading. In use the pyrometer is held up to the eye and directed towards the hot object. If the filament has a brighter colour than the object it is visible as a lighter line against a

dark background ; if the object is lighter than the filament the filament is seen as a darker line against a light background. By adjusting the screw one way or the other a point is reached when the filament can no longer be seen ; it has then exactly the same colour as the background, and from the galvanometer needle and scale the temperature of the filament, and consequently that of the object, can be read.

Another type of pyrometer makes use of a couple of dissimilar metals in the form of long rods, connected to each other at the outer end and by wires at the handle end to a galvanometer whose scale is graduated in degrees of temperature. A weak electric current is generated by the contact of the two metals and this varies in intensity with difference in the temperature of their two extremities. The outer end of the double rod is placed in the kiln, etc. until it has assumed its temperature and the galvanometer then registers the current and the corresponding temperature. Still another pyrometer measures the variation of resistance to electric current which metals exhibit at different high temperatures.

A pyrometer, as the name implies, is an instrument for measuring the temperature of *fires*. It is thus only of service when extremely high temperatures are involved. The contrivance utilizing the principle of change of hardness or viscosity is the fusible cone. These cones are made of certain clays which fuse and commence to flow at different temperatures. A range of the cones is introduced into the kiln whereupon some melt and others do not, so indicating the approximate temperature. These again are only of use for very high temperatures, and for general purposes are unsuitable.

**THERMOMETERS.**—By far the most convenient method is one utilizing the change in volume undergone by materials on change of temperature. Such an instrument is called a *thermometer*. A block of metal expands upon being heated and contracts upon cooling, but this movement is very slight and, being volumetric, difficult of measurement. If, however, the metal were in the form of a long, thin rod or wire its change of *length* could be measured, its movement in the other dimensions being then negligible. Such a principle is drawn into service, but not so much for the measurement of temperature as for the operation of light mechanisms, or for making or breaking electrical contact, upon a definite temperature being reached.

A certain type of thermometer does, however, make use of the fact that all metals do not expand and contract equally for a given temperature change. If two strips of different metals, say iron and aluminium, are secured together throughout their length and then heated, the aluminium becomes longer than the iron. As it is secured to the iron it

cannot increase in length except by bending both strips through an arc ; this movement may be made to actuate a small rod which turns a needle over a dial graduated to give readings of temperature. A more accurate " bi-metallic " type of thermometer has the composite strip in the form of a spiral which is caused to wind and unwind by the unequal expansion, actuating a pointer as before. Such instruments are mostly in use as adjuncts to ovens, etc., and not for general purposes.

Early thermometers made use of a column of air in a glass tube and were very sensitive, but as they were affected by weather conditions they have been superseded by liquid thermometers. Nevertheless for extremely low temperatures hydrogen thermometers are used, but corrections have to be made for changes of atmospheric pressure.

**LIQUID THERMOMETERS.**—A *liquid thermometer* consists of a glass tube of very fine but uniform bore, with its lower end enlarged into a bulb to contain the liquid. Upon being heated the liquid expands and rises up the bore of the tube, falling again upon cooling. Thus, although the movement is volumetric, we actually measure the length or height of a thin column of the liquid. To obviate spilling, the top of the tube is sealed but before this is done all air must be evacuated or, being enclosed, it would offer resistance to the rise of the liquid.

To perform the actual measurement, units must be devised and marked along the tube in the form of a scale, but this graduation must for uniformity start from a fixed low point corresponding to a definite, unvarying temperature. If all thermometer bulbs were of the same size and the bores of the same diameter this one fixed point would be sufficient to ensure uniformity. But as this is not the case a second (high) fixed point is necessary. For any size of bulb and bore of tube the length of tube between two such fixed points then represents the same range of temperature. If this be divided into the same number of equal parts, numbered in the same manner, all such thermometers will give identical readings for the same temperature, irrespective of the actual length of scale.

The obvious lower fixed point to adopt is that corresponding to complete absence of heat. This point was not known when the three recognized temperature scales were devised, besides which these very low temperatures are not normally met with, and so we find that in two of such scales the point adopted is the melting point of ice. This temperature is for practical purposes constant and the same everywhere, and so is quite as convenient.

The higher fixed point is the temperature of the steam issuing from boiling water. This temperature is not the same under all conditions, varying as it does with the purity of the water and with the pressure of



the air in which boiling takes place. The standard temperature is that of pure water boiling in an atmospheric pressure equivalent to that of 30-in. or 760-mm. of mercury.\*

Having decided upon the lower and higher fixed points it remains to divide the space between them into a number of equal parts and to continue this graduation over the whole length of the tube in the form of a scale. They are called *degrees* of temperature.

The *Centigrade* scale has the lower point marked zero and the higher point 100 degrees, the space between thus divided into 100 equal parts. Degrees below zero are considered minus or negative. This scale is almost universally used for scientific purposes and in most countries for ordinary purposes too.

The *Reamur* scale is similar except that the high fixed point is called 80 degrees. It has been used for ordinary purposes in a few countries of Europe but its use is dying out in favour of the Centigrade scale.

The *Fahrenheit* scale, much used once, has now been abandoned except by Great Britain where it is still used for ordinary purposes in preference to the Centigrade scale. Fahrenheit, in the eighteenth century, took as his two fixed points *a* the temperature of an ice-salt mixture which he thought was the lowest temperature obtainable, and *b* the temperature which he thought was the normal blood temperature. These he called 0 and 96 degrees respectively, and by continuing the scale the melting point of ice becomes 32 degrees and the temperature of steam at standard pressure 212 degrees.

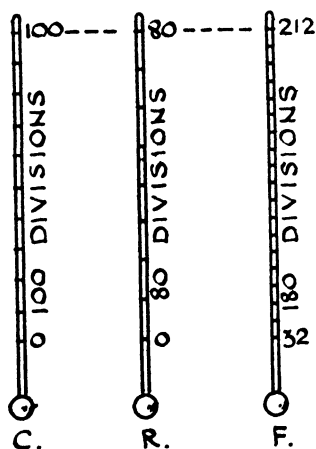


FIG. 293.—The Thermometer Scales compared.

Fig. 293 shows the three scales compared. Although we invariably use the Centigrade (C.) scale in science the Fahrenheit (F.) scale is still in use for domestic and medical purposes and in heating and ventilating. A common requirement therefore is for the conversion of a C. reading into a F. reading, and *vice versa*. This is not difficult if the two scales are visualized side by side, remembering that 1 C. degree = 1.8 F. degrees and that 0 C. = 32 F.

Thus F. reading =  $(C. \times 1.8) + 32$

and C. reading =  $\frac{F. - 32}{1.8}$

(\* The meaning of this will be clear after reading Chapter XXIV.)

**EXAMPLE.**—Convert 57 deg. F. to Centigrade.

$$C. = \frac{F. - 32}{1.8} = \frac{57 - 32}{1.8} = \underline{13.9 \text{ deg. C.}}$$

**EXAMPLE.**—Convert 42 deg. C. to Fahrenheit.

$$F. = (C. \times 1.8) + 32 = (42 \times 1.8) + 32 = \underline{107.6 \text{ deg. F.}}$$

The liquids most commonly used in liquid thermometers are alcohol and mercury. Alcohol is coloured to make it more easily visible. Its advantage is that it freezes at  $-130$  deg. C. and may therefore be used to measure low temperatures, but it has a disadvantage in that its boiling point is only  $78$  deg. C. Mercury is the best liquid for general purposes. Its range is from  $-38.9$  to  $357$  deg. C. and it does not adhere to the inside of the tube.

In use a very slight error may be introduced owing to the fact that only the bulb, and perhaps a part of the stem, is immersed instead of the whole instrument.

If the thermometer be suddenly immersed in hot liquid the mercury level may be seen momentarily to fall slightly. This is because the glass first expands, so slightly increasing its capacity before the heat has reached the mercury and started its expansion.

**THERMOCOUPLES.**—The name *thermocouple* or *thermo-electric thermometer* is given to any instrument whereby temperatures are measured from the electromotive force generated in a circuit. The pyrometer mentioned on page 324 is an example.

When two wires of different metals are connected at both ends they form an electrical circuit, and if the two connections are at different temperatures a current flows through it. By including in the circuit a suitable galvanometer or millivoltmeter the current flowing may be measured. The amount of current depends not only upon the difference between the temperatures of the two connections but also upon the pair of metals used, the choice of these depending upon the order of the temperatures to be measured. A galvanometer, etc. used expressly for this purpose is invariably calibrated to give direct readings of temperature.

As architects and builders, thermocouples need not bother us further except for the type known as the *thermopile*. This is really a battery of small thermocouples connected in series and of metals suitable for low temperatures, usually bismuth and antimony or bismuth and silver. The more pairs of bars the stronger is the induced current, but this is governed by the size and portability of the instrument. It is seen in use in Fig. 344 for measuring the electric current produced as a result of heat radiation falling on one set of connections exposed in the base of the "trumpet." The other set, at the back, is protected from the radiation

by a brass cover or cap, and the special galvanometer is provided with a scale giving centigrade temperatures corresponding to the readings of current.

### 3. MEASUREMENT OF HEAT.

In the measurement of heat, just as in measuring length, etc., it is necessary to adopt a unit. The unit of heat may therefore be the amount of heat necessary to raise a definite mass of a standard substance through a definite range of temperature, or alternatively the amount of heat given out by a definite mass of a standard substance when cooled through a definite range of temperature.

**UNITS OF HEAT.**—In the Metric system the heat unit is the *calorie* and is *the amount of heat necessary to raise the temperature of 1 gram of water 1 deg. Centigrade*.

The British unit is the *British Thermal Unit* or B.Th.U.\* and is *the amount of heat necessary to raise the temperature of 1-lb. of water 1 deg. Fahrenheit*.

The two units are not comparable in amount for, although the F. degree is only  $\frac{5}{9}$  of a C. degree, the lb. is equivalent to 454 gm. The B.Th.U. is thus approximately 252 times as great as the calorie, and in practical problems in heating, etc., is much more manageable. Because of this the Metric unit used in such work is taken as the quantity of heat required to raise 1 kilogram of water through 1 deg. C., equivalent to 1,000 calories, and called the *kilogram-calorie* or the *gram-calorie*. It will be seen to be roughly equal to 4 B.Th.U.

**EXPERIMENT 131.**—To show that the amount of heat in a body depends upon its mass.

Take two beakers of about 250 c.cm. capacity, place equal quantities, say 200 c.cm. of cold water in each, and rest a thermometer in each after recording their temperatures, which should be equal. Now take a third vessel about two-thirds full of water and bring it to boiling point. Cut two pieces of stout sheet lead, one say about 2 sq. in. and the other 2 to 3 times this size. Bore a hole in one corner of each piece, attach a thread and place them in the boiling water. Let them remain for several minutes so as to attain the temperature of the water and then, by the thread, transfer each quickly to one of the beakers of cold water. Stir with the thermometer and note the *maximum* reading in each case.

The water to which the larger piece of lead is added will reach a higher final temperature than the other, although both pieces were of the same temperature and were added to cold water of identical temperature.

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(\* NOTE.—Not B.T.U. which is the accepted abbreviation of Board of Trade Unit).

**EXPERIMENT 132.**—To show that the amount of heat in a body depends upon its temperature.

Take two beakers of cold water as before, placing a thermometer in each after recording their temperature. Now take two pieces of lead of equal weight, heat one in boiling water and the other in water maintained at, say, 50 deg. C. Transfer each to the cold water, stir and take the final (maximum) thermometer reading as before.

The piece heated to 100 deg. C. will heat the cold water to a higher temperature than will the piece heated to only 50 deg. C.

Actually, the amount of heat is proportional to the mass of the body and to the range of temperature. Thus the amount of heat necessary to raise the temperature of 2 gm. of water through 1 deg. C. is 2 calories, to raise 20 gm. of water 1 deg. C. 20 calories, etc. Also to raise the temperature of 1 gm. of water through 2 deg. C. 2 calories are necessary, 1 gm. through 20 deg. C. 20 calories, etc. Further, for practical purposes, 20 calories represents the amount of heat necessary to raise 1 gm. of water from 0 deg. C. to 20 deg. C., or from 20 deg. to 40 deg., or from 74 deg. to 94 deg., etc., etc.

**THERMAL CAPACITY.**—So far we have been considering the effect of the mass and temperature of the same substance, (lead in Experiments 131 and 132), upon the amount of heat. Let us now consider different substances.

**EXPERIMENT 133.**—To show that substances differ in their "capacity for heat."

As before take two beakers containing equal quantities of cold water, say 100 c.cm. Now place 100 gm. of water into a third beaker together with a solid body weighing 100 gm.—a 100-gm. brass weight on the end of a thread is suitable—and heat to boiling point. Have a thermometer in each cold water beaker, record the temperature, and then quickly remove the brass weight from the hot water and drop it into one of the beakers. At the same time pour the hot water into the other beaker, stir both mixtures with the thermometers and observe the maximum readings. The water-water mixture will be found to be much hotter than the water-brass mixture.

In this experiment, although equal masses of water and brass were heated to the same temperature, they clearly "absorbed" different amounts of heat because they "yielded" different amounts of heat to the cold water when mixed with it. This different "capacity for heat" possessed by different substances is called their *thermal capacity*. *The thermal capacity of a substance is the amount of heat necessary to raise unit mass of the substance through 1 degree of temperature, say 1 gm. through 1 deg. C.*

**SPECIFIC HEAT.**—We have just seen that different materials have different thermal capacities, in the same way as they may have different densities, etc. In the case of density we relate the density of a material to that of a standard material—water—and so obtain a relative density or *specific gravity*. Similarly we may relate the thermal capacity of a substance to that of a standard substance and so obtain a relative thermal capacity or *specific heat*.

Whilst density must be expressed in units specific gravity is a ratio or number. Thermal capacity must also be expressed in units but specific heat is a ratio or number. *The specific heat of a substance is the ratio between the amount of heat necessary to raise a given mass of the substance through a given range of temperature and the amount of heat necessary to raise an equal mass of water through the same range of temperature.*

As in the case of density so with thermal capacity water is the standard substance, and as its thermal capacity is greater than that of any other substance (except certain gases) their specific heats are less than unity, as is shown in Table 16.

TABLE 16.

SPECIFIC HEATS OF COMMON SUBSTANCES.

Substance	S.H.	Substance	S.H.
Water .. .. .	1·00	Glycerine .. .. .	·57
Air .. .. .	·237	Iron .. .. .	·114
Alcohol .. .. .	·62	Lead .. .. .	·031
Aluminium .. .. .	·215	Mercury .. .. .	·033
Brass (av.) .. .. .	·093	Tin .. .. .	·055
Copper .. .. .	·095	Zinc .. .. .	·094
Glass .. .. .	·15	Hydrogen .. .. .	3·409

Now, as the amount of heat necessary to raise 1 gm. of water 1 deg. C. is 1 calorie, *the specific heat of any substance is numerically identical with the number of calories necessary to raise 1 gm. of the substance 1 deg. C.*

**SPECIFIC HEAT BY METHOD OF MIXTURES.**—If, in Experiment 133, loss of heat could be entirely prevented between the times of reading the temperature of the hot water and that of the final mixture of hot and cold, then the amount of heat lost by the hot to the cold water would be exactly equal to the amount gained by the cold from the hot water.

This fact enables us to determine experimentally the specific heat of a substance by what is known as the Method of Mixtures. If we mix

equal quantities of water at 0 deg. C. and 60 deg. C. respectively the mixture ultimately reaches a temperature midway between 0 and 60, *i.e.* 30 deg. C. For each degree fall in temperature of the hot water the cold water has risen one degree, until both are at 30 degrees. Thus :—

<i>Hot water</i>	<i>Cold water</i>
60 deg. C.	0 deg. C.
59 „	1 „
58 „	2 „
57 „	3 „
.	.
.	.
.	.
.	.
33 „	27 „
32 „	28 „
31 „	29 „
30 „	30 „

Now suppose we mix water and another substance, say iron whose thermal capacity is roughly  $\frac{1}{9}$  that of water (see Table 16). On heating the iron to 60 deg. C. and placing it in an equal mass of water at 0 deg. C. the water rises only  $\frac{1}{9}$  deg. for each fall of 1 deg. of the iron, 1 deg. for each 9 deg. etc., etc. Thus :—

<i>Iron</i>	<i>Water</i>
60 deg. C.	0 deg. C.
51 „	1 „
42 „	2 „
33 „	3 „
24 „	4 „
15 „	5 „
6 „	6 „

The temperatures of the iron and water are now equal and, as the specific heats of iron and water are known, the final temperature can be calculated. Conversely, as in experimental work, if the final temperature and the specific heat of one of the substances (the water in this case) is known, the specific heat of the other substance can be calculated.

**EXAMPLE.**—50 gm. of aluminium at 100 deg. C. is placed in 100 gm. of water at 20 deg. C. On stirring with a thermometer the temperature of the mixture is observed to be  $27\frac{1}{4}$  deg. C. Find the specific heat of the aluminium.

$$\begin{aligned}
 \text{Amount of heat lost by aluminium} &= 50 \times \text{S.H.} \times (100 - 27\frac{1}{2}) \\
 &\qquad\qquad\qquad \text{calories.} \\
 &= \text{Amount of heat gained by water} = 100 \times 1 \times (27\frac{1}{2} - 20) \\
 &\qquad\qquad\qquad \text{calories.} \\
 \text{Therefore S.H. (of the aluminium)} &= \frac{100 \times 1 \times 7.75}{50 \times 72.25} = \underline{\underline{.214}}
 \end{aligned}$$

In experimental work, however, we cannot prevent some loss of heat to the air and to the portion of the thermometer immersed in the water for the purpose of stirring and reading the temperature. More important still is the fact that the vessel used for the mixing absorbs an appreciable amount of heat, although this can be allowed for. In accurate work this vessel is of polished copper and is called a *calorimeter*. It is placed inside a larger vessel and the space between the two packed with cotton wool, granulated cork or other such material suitable to reduce heat loss from the outer surface of the calorimeter. If we know the mass of the calorimeter ( $M$  gm.) and its specific heat (S.H.) then the amount of heat which it absorbs through any range of temperature ( $t$ ) is equal to  $(M \times \text{S.H.} \times t)$  calories. The quantity of water that would absorb this amount of heat through the same temperature range is equal to  $(M \times \text{S.H.})$  gm. If therefore we calculate  $(M \times \text{S.H.})$  for a particular calorimeter made of copper and weighing 56 gm. we get  $M \times \text{S.H.} = 56 \text{ gm.} \times .095 = 5.32 \text{ gm.}$  This is called the *water equivalent* of the calorimeter, for if it were possible to have the vessel made of material of the same specific heat as water and weighing 5.32 gm. it would absorb the same amount of heat as does the copper vessel weighing 56 gm.

The water equivalent of the calorimeter added to the *actual* quantity of water used gives us the total *equivalent* quantity of water that is absorbing the heat in the experiment.

**EXPERIMENT 134.**—To determine the S.H. of lead, by the method of mixtures.

For heating the lead it is not sufficiently accurate to heat it in water as we then transfer some water to the calorimeter along with the lead. There are many types of heater designed to keep the solid dry and to permit of its transfer with a minimum of delay. Fig. 294 shows a simple type quite suitable for small solids and which may be made from a "tin" container.

The solid should be of such form as to give up its heat rapidly to the water: in this case a piece of thin sheet or a quantity of shot is better than a thick block.

The lead, we will assume in the form of shot, is weighed and placed in the heater. Whilst heating is in progress the calorimeter is weighed, if its weight is not already known, half-filled with cold water, weighed again and the weight of water found by subtraction. When the thermometer in the heater shows a steady reading it may be taken that the lead has assumed the temperature of the boiling water. Now read and record the temperature of the cold water,

remove the test tube from the heater, take out the cork and thermometer, wipe the test tube quickly to dry it and pour the shot into the calorimeter stirring gently with the thermometer and noting the maximum reading. Set out the results as shown below.

Weight of calorimeter	=	58.86 gm.
Water equivalent = $58.86 \times .095$	=	5.59 gm.
Weight of calorimeter and water	=	89.62 gm.
Weight of water = $89.62 - 58.86$	=	30.76 gm.
Total equivalent weight of water = $58.86 + 5.59$	=	64.45 gm.
Weight of lead shot	=	51.21 gm.
Temperature of lead shot	=	99 deg. C.
Temperature of cold water	=	14.5 deg. C.
Temperature of mixture	=	16.5 deg. C.
Heat lost by lead	=	Heat gained by water
$M \times \text{S.H.} \times t$ calories	=	$M \times \text{S.H.} \times t$ calories
$51.21 \times \text{S.H.} \times (99 - 16.5)$	=	$64.45 \times 1 \times (16.5 - 14.5)$
$51.21 \times \text{S.H.} \times 82.5$	=	$64.45 \times 2$
Therefore S.H. = $\frac{64.45 \times 2}{51.21 \times 82.5}$	=	<u>.031</u>

The specific heat of a liquid may be found by a modification of the same method. The cold liquid is placed in the calorimeter in lieu of the water and the solid to be heated is one of known specific heat.

EXPERIMENT 135.—To determine the S.H. of turpentine by the method of mixtures.

Weight of calorimeter	=	58.86 gm.
Water equivalent	=	5.59 gm.
Weight of calorimeter and turpentine	=	95.06 gm.
Weight of turpentine = $95.06 - 58.86$	=	36.2 gm.
Weight of lead shot	=	184.34 gm.
S.H. of lead shot (assumed)	=	.031 gm.
Temperature of lead shot	=	99 deg. C.
Temperature of calorimeter and turpentine	=	17 deg. C.
Temperature of mixture	=	34 deg. C.
Heat lost by lead	=	Heat gained by turpentine and calorimeter
$M \times \text{S.H.} \times t$	=	$M$ (of turpentine) $\times$ S.H. $\times t$ + Water equivalent $\times t$
$184.34 \times .031 \times (99 - 34)$	=	$36.2 \times \text{S.H.} \times (34 - 17)$ + $5.59 \times (34 - 17)$
371.4	=	S.H. $\times 615.4 + 95.03$
Therefore S.H. = $\frac{371.4 - 95.03}{615.4}$	=	$\frac{276.37}{615.4} = $ <u>.44</u>

SPECIFIC HEAT BY METHOD OF COOLING.—There are several other methods whereby the specific heat of a substance may be found, but the method of mixtures is the most convenient and the simplest method for solids. For liquids the Method of Cooling is perhaps the best and will be described.



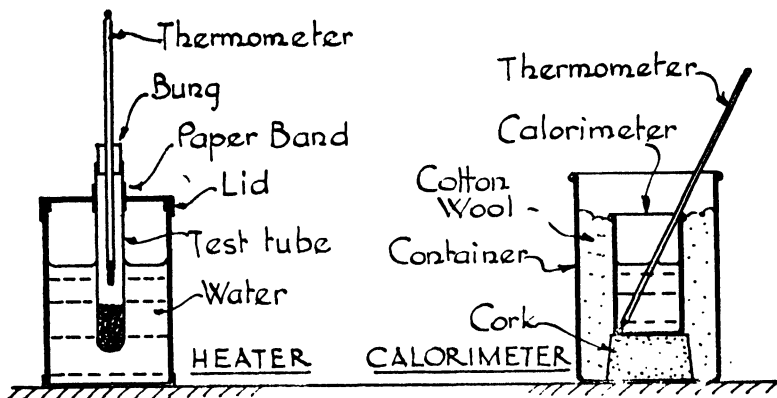


FIG. 294.—Simple Heater and Calorimeter.

The apparatus required is a copper calorimeter, with a hole through the lid to accommodate a thermometer. This is rested on a large diameter cork inside a larger vessel with lid which prevents draughts of air during cooling.

**EXPERIMENT 136.**—To determine the S.H. of paraffin by the method of cooling.

Weigh the calorimeter (its specific heat is  $\cdot095$ ), place in it a definite volume of hot water, say 50 c.cm., insert the thermometer, and note the time taken to cool through say 10 deg. C. (Several 10 deg. intervals should be observed—60—50, 50—40, etc., and the water should be gently stirred whilst the readings are being taken). When it has cooled to room temperature weigh the calorimeter and water, so obtaining the mass of the water.

Now repeat with approximately the same mass of hot paraffin, noting the rate of cooling over the same temperature ranges. Again, after cooling, weigh the calorimeter and paraffin to obtain the mass of the paraffin.

Mass of calorimeter, stirrer and lid	= 138.551 gm.
S.H. of calorimeter	= $\cdot095$
Mass of water = 186.953 — 138.551	= 48.402 gm.
Time of cooling from 60 to 50 deg.	= 16.5 min.
Time of cooling from 50 to 40 deg.	= 22 min.
Mass of paraffin = 185.81 — 138.551	= 47.259 gm.
Time of cooling from 60 to 50 deg.	= 10½ min.
Time of cooling from 50 to 40 deg.	= 14 min.

Now, as the thermal capacities are inversely proportional to the rates of cooling,

$$\begin{aligned}
 & \frac{\text{Mass of water} + (\text{mass of calorimeter} \times \cdot095)}{\text{Time to cool water through 10 deg. C.}} \\
 & = \frac{(\text{Mass of paraffin} \times \text{S.H.}) + (\text{Mass of cal.} \times \cdot095)}{\text{Time to cool paraffin through 10 deg. C.}} \\
 & \text{Therefore S.H.} = \frac{26.01}{47.259} = \underline{\underline{\cdot55}}
 \end{aligned}$$

**SIGNIFICANCE OF SPECIFIC HEAT OF A MATERIAL.**—On reference to Table 16 (page 330) the specific heats of alcohol and mercury are seen to be  $\cdot 62$  and  $\cdot 033$  respectively, whilst that of water is  $1\cdot 00$ . This indicates a further advantage of mercury for use in liquid thermometers, the mercury absorbing very little heat from the substance whose temperature is being determined. Alcohol would absorb roughly twenty times as much heat and water roughly thirty times as much.

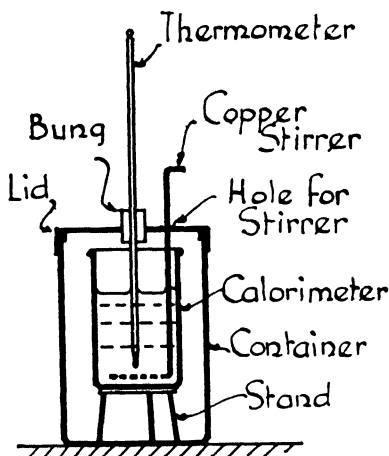


FIG. 295.—Cooling Calorimeter.

The specific heat of water is much higher than that of other liquids. For a given rise in temperature it absorbs much more heat than does an equal mass of any other liquid, and for a given fall of temperature it gives out more heat. For this reason it is the most suitable liquid for use in a circulatory cooling system such as that of an internal combustion engine. Occasionally, however, its liquid range ( $0$ – $100$  deg. C.) is insufficient for the purpose required, as in the case of aircraft engines, and it may then be replaced by glycerine whose liquid range is  $-17$  to  $290$  deg. C., at the sacrifice however of thermal capacity. (S.H. of glycerine  $\cdot 57$  as against S.H. of water  $1\cdot 00$ ).

In this instance the requirement is to remove unwanted heat and dissipate it. In the warming of buildings by circulation the problem is somewhat similar. For convenience the heat is generated by a furnace at one point in the building and conveyed by a suitable liquid medium to other parts by pipes and "radiators," by means explained in Chapter XXII. Water is the liquid always used, not because of its cheapness or ready availability, but because of its high specific heat. If there happened to be a liquid with a specific heat of 10 or 20 it would obviously be used in preference to water provided that it was suitable in other respects,

even if expensive to buy. Note that we have to put into the water more heat than we should have to put into an equal volume of other liquids—from this point of view there is no advantage except of cheapness and availability—the great advantage is that smaller pipes, etc. may be used, at less cost, because for a given quantity of heat less water has to be conveyed than would be the case if other liquids were used.

**Exercises.**

1. Convert  $-4$  deg. C. to Fahrenheit. (Ans.  $24.8$  deg. F.)
2. Convert  $206$  deg. F. to Centigrade. (Ans.  $96.33$  deg. C.)
3. Convert  $400$  B.Th.U. to kilogram-calories. (Ans.  $100.9$  k.-cal.)
4. How many B.Th.U.s are required to raise the temperature of  $300$  gm. of copper from  $0$  deg. C. to  $140$  deg. C. ? (Ans.  $15.82$  B.Th.U.)
5. Construct a graph for the conversion of Fahrenheit to Centigrade readings.
6. Construct a graph for the conversion of calories to British Thermal Units.
7.  $500$  gm. of metal having a specific heat of  $.1$  is heated to  $99$  deg. C. and placed in water at  $15$  deg. C. If the final temperature reached is  $23$  deg. C. how much water is used ? (Ans.  $500$  gm.)

## TEMPERATURE MOVEMENT

1. *Expansion and Contraction of Solids.*
2. *Expansion and Contraction of Liquids.*
3. *Expansion and Contraction of Gases.*
4. *Effects of Temperature Movement.*
5. *Temperature Movement related to Strain and Moisture Movement.*

## 1. EXPANSION AND CONTRACTION OF SOLIDS.

It has been pointed out (page 322) that one of the effects of heat upon a body is a change of volume, and therefore density. When we increase the heat motion of the molecules of a body they take up more space and this normally results in expansion of the body. If the body is isotropic in structure this expansion will be equal in all dimensions. Metal, glass, brick, some stones, liquid and gas are all isotropic, for their structure is identical in all three dimensions. Timber is an example of a material which is not isotropic on account of its grain.

**VOLUMETRIC EXPANSION OF SOLIDS.**—If a metal sphere is heated it expands equally in all directions and so remains spherical. Similarly a cube would remain a perfect cube, if heated uniformly. A couple of simple experiments may be carried out to show the volumetric expansion of solids.

**EXPERIMENT 137.**—The “ Ball and Ring ” experiment.

The apparatus comprises a circular brass ring with handle attached and a brass sphere which just passes easily through the ring when cold. The sphere is heated in a Bunsen flame and will then no longer pass through the ring no matter which way it is turned.

If held for some time it will again fall through the ring on contraction due to cooling or when the ring has assumed the temperature of the sphere by contact and so expanded.

**EXPERIMENT 138.**—To show the volumetric expansion of a cylinder.

Fig. 297 shows a short brass rod and gauge, the distance between the jaws being such that when cold the rod is just a sliding fit, and the diameter of the circular hole such that when cold the end of the rod may be inserted. On heating the rod neither will be found possible, thus showing that it has expanded both in length and in cross section. After cooling it may again be pushed in.

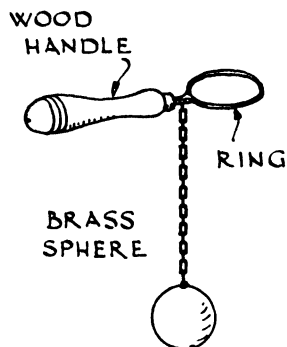


FIG. 296.—The Ball and Ring Apparatus.

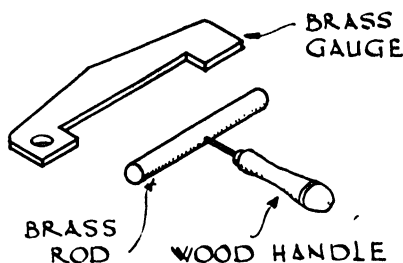


FIG. 297.—The Rod and Gauge Apparatus.

**SUPERFICIAL EXPANSION OF SOLIDS.**—In the case of relatively thin sheets of material the expansion or contraction in the direction of the thickness is negligible by comparison with that in the other directions. We refer to expansion in two directions as expansion of area or *superficial expansion*. Its practical importance is in the fixing of extensive sheets of material such as metal, glass, plywood, renderings, etc. Only in the case of metal, glass and other dense materials is temperature movement liable to require precautionary measures. Timber, plasters, etc., expand and contract, but because of contained moisture rather than by temperature change. In fact when we heat such materials they usually *contract* owing to the drying out of some of their sorbed moisture. (See Chapter IV.) Only when they are almost perfectly dry is expansion apparent, and then it is only very slight owing to their high porosity.

**LINEAR EXPANSION OF SOLIDS.**—Of far greater importance than volumetric or superficial expansion is *linear expansion*. Instances abound in Building where the cross section of a member, etc. is negligible by comparison with the length. Expansion and contraction in the direction of the length is then by far the most important. Beams, pillars, members of frames, framed structures themselves, pipes, walls (especially those of monolithic concrete), measuring chains, are all examples.

As with the mercury in the mercury thermometer the expansion of other substances is as a rule uniform: in other words the increments of expansion for each degree rise of temperature are almost equal, so nearly equal that the rate of movement is taken to be uniform.

**EXPERIMENT 139.**—To show that linear expansion is proportional to rise in temperature.

Fig. 298 shows the apparatus required but a few points need especial emphasis. All bungs should be tightly fitted as there is some internal water pressure acting on the whole apparatus. The

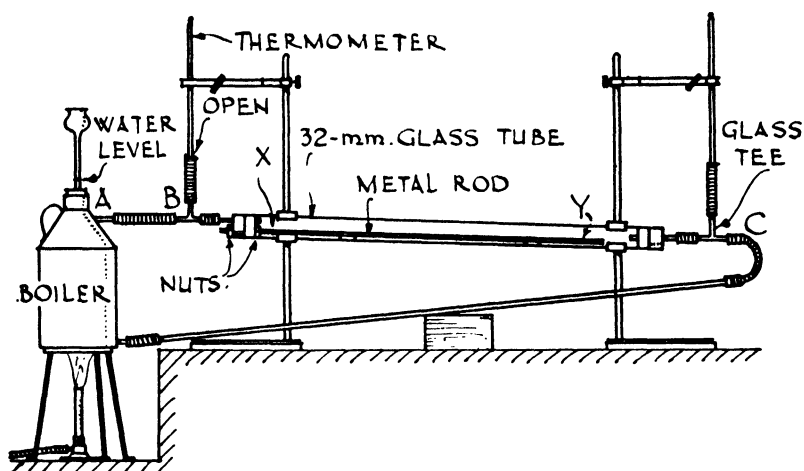


FIG. 298.—To Show Relationship between Linear Expansion and Temperature Rise.

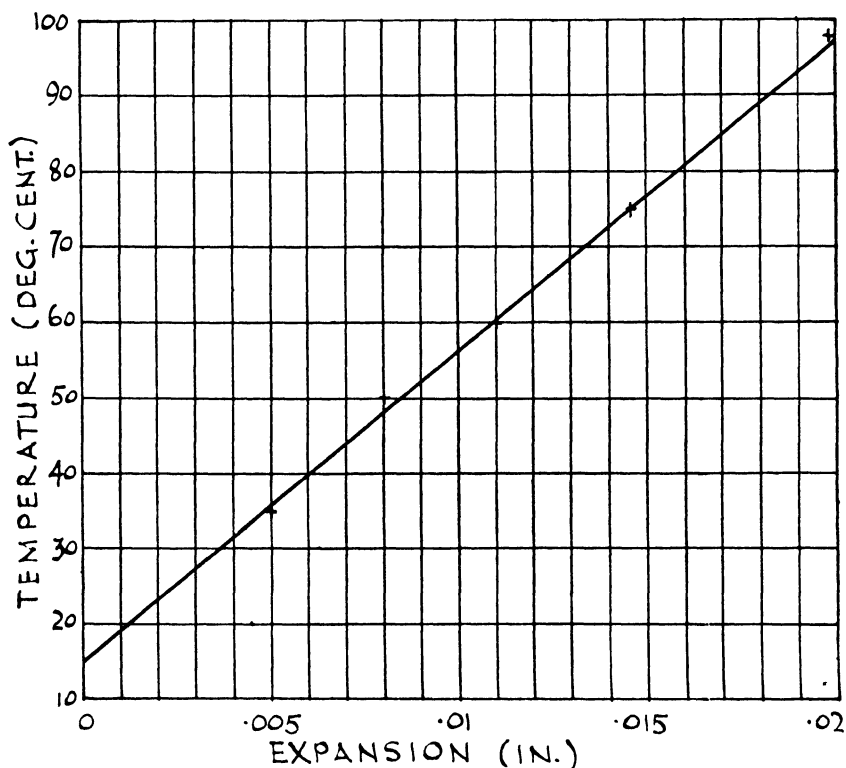


FIG. 299.—Graph showing Proportionality of Expansion to Temperature Rise.

water level must be maintained so as to fill completely the large diameter glass tube, but not too high up the thistle funnel or increased pressure will result, with a possibility of leakage at some point. The mark shown in the diagram is approximately correct. There must be a slight rise from A to B and then a slight fall to C, otherwise air may be trapped in the large tube and cause trouble.

The specimen is a straight metal rod  $\frac{1}{8}$ -in. or  $\frac{3}{16}$ -in. in diameter, threaded for about  $1\frac{1}{2}$ -in. at one end, supported in the tube on shaped wood blocks, and secured at one end by nuts to the bung. The other end is left free to move. Two marks are made on the rod, one near to each end; the distance between them being the "original length."

Read both thermometers before heating the water and then fix a travelling microscope so that it may be focussed on to mark Y and take the initial reading on its scale by means of the vernier. Then apply heat gently to the boiler and when the temperature of the water has risen about 20 deg. C. take both thermometer readings afresh (taking the mean temperature) and a new reading on to mark Y. Repeat this procedure at intervals and plot the results in the form of a graph such as the one shown in Fig. 299

**COEFFICIENTS OF LINEAR EXPANSION (OR CONTRACTION).—**The actual expansion of most solids is relatively slight, usually so little as to be imperceptible except by fine measurement, nevertheless its effects may be serious, even disastrous, in practice.

For the purpose of calculation the amount of expansion undergone by a unit length of the solid for a rise in temperature of 1 degree is taken as a coefficient. It is called the *coefficient of linear expansion* for the particular material and is equal to

$$\frac{\text{Total expansion}}{\text{Original length} \times \text{temperature rise.}}$$

The coefficient will clearly depend upon the temperature scale used, but unless otherwise stated it is always Centigrade. The original length and expansion may be in any units but so long as they are measured in the same units the value of the coefficient is not affected.

**EXPERIMENT 140.**—To determine the coefficient of linear expansion of copper, iron, brass, etc.

For metals such as steel, copper, brass, etc. the apparatus shown in Fig. 300 may be used, the expansion being measured direct by means of a precision instrument such as a micrometer, vernier calliper, vernier microscope, etc.

The specimen consists of a special tube of the particular metal which fits through holes in the upright blocks at each end of the baseboard. Between the blocks the tube is surrounded by another tube of asbestos which acts as a jacket to minimize loss of heat. One end of the metal tube is clamped at A by a screw and the other end is left free, but a loose block fitting over the tube is clamped to it at B.

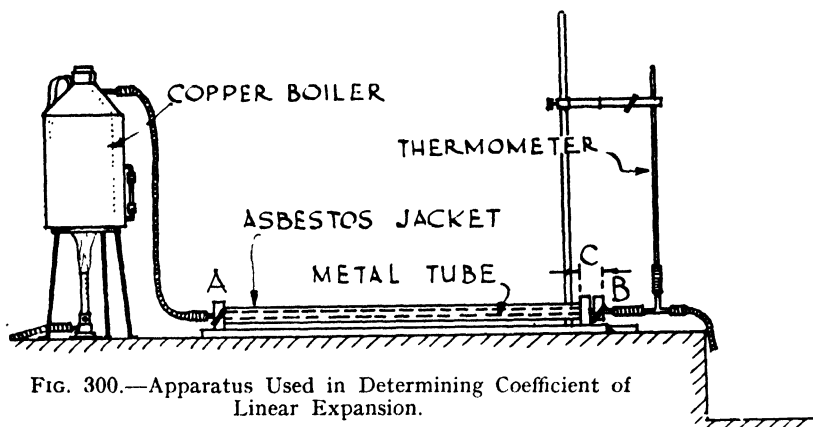


FIG. 300.—Apparatus Used in Determining Coefficient of Linear Expansion.

Cold water is first run through whilst only A is clamped, and the temperature of the water taken. The sliding block B is now placed tightly up to the other block so that there is no gap, the screw B tightened and the overall width of the two blocks measured with micrometer, etc. (If a microscope is used for measurement the gap may be measured directly). The distance from centre to centre of the two clamping screws is now measured; this is the "original length."

Steam is now passed through the tube causing it to expand. As end A is fixed the movement is towards B and a gap will be seen to open between the two blocks at this end. The new temperature is now read and the new overall width C measured.

The various readings for copper tube were :—

Initial temperature	= 16.2 deg. C.
Final temperature	= 99.6 deg. C.
(Mean between 100 deg. and thermometer reading.)	
Rise in temperature = 99.6 — 16.2	= 83.4 deg. C.
Initial reading at C	= 1.5 cm.
Final reading at C	= 1.507 cm.
Expansion = 1.507 — 1.5	= .007 cm.
Original length	= 50 cm.

Therefore coefficient of linear expansion

$$= \frac{\text{Expansion}}{\text{Original l} \times \text{temp. rise.}} = \frac{.007}{50 \times 83.4} = .0000167$$

For a soft metal such as lead this apparatus is not suitable and the apparatus shown in Fig. 68 (page 87), and used to show moisture movement, may be used. The specimen in this case is a bar of cast lead  $\frac{1}{2}$ -in.  $\times$   $\frac{3}{8}$ -in.  $\times$  12-in. long or a length of flattened lead pipe of about the same cross dimensions.

**EXPERIMENT 141.**—To determine the coefficient of linear expansion of lead.

The tank is shown in Fig. 301, the arrangement for holding the specimen and measuring the expansion being here omitted for clearness (see Fig. 68).



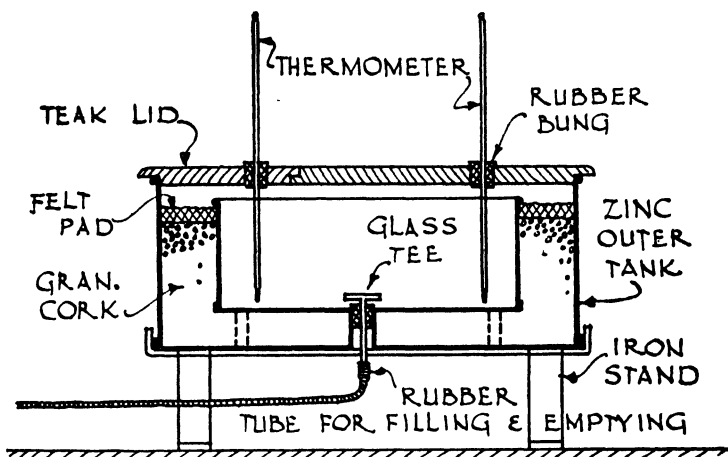


FIG. 301.—Alternative Method of Determining Coefficient.

To use the apparatus clamp the specimen between the invar steel bars, placing the rollers in position at the free end. Place this in the empty tank, fit the wooden lid with its thermometers, and arrange the horizontal pointer and scale. Run in cold water through the bottom of the tank, record the temperature and place the scale so as to give zero reading. Then release the cold water and by connecting the rubber tube to a copper boiler full of hot water admit this to the tank. Again read the temperature and also the movement of the pointer across the scale. The actual increase in length over the original length of 10-in. is  $\frac{1}{1024}$  of the scale reading.

The readings for a bar of cast lead were :—

Initial temperature	= 17.5 deg. C.
Final temperature	= 41 deg. C.
Temperature rise = 41 — 17.5	= 23.5 deg. C.
Scale reading of expansion	= 6.9 in.
Actual expansion = $\frac{6.9}{1024}$	= .0067-in.

Therefore coefficient of linear expansion

$$= \frac{\text{Expansion}}{\text{Original l} \times \text{Temp. rise.}} = \frac{.0067}{10 \times 23.5} = .0000285.$$

It may be objected that the expansion recorded in this experiment is not the real expansion because the two bars which hold the specimen and give the original length of 10-in. also expand at the same time. This is so only to a very limited extent since they are made of *invar* steel, a nickel steel containing 36 per cent. nickel, whose coefficient is only .0000009. Its expansion is therefore negligible (less than  $\frac{1}{10}$  that of the lead), but if desired it may be calculated and taken into account.

Invar is therefore a most useful metal to use for measuring tapes and chains, pendulums and balance wheels, in fact for any purpose where appreciable temperature movement would be a disadvantage.

TABLE 17.

COEFFICIENTS OF LINEAR EXPANSION (Centigrade).

<i>Material</i>	<i>Coefficient</i>	<i>Material</i>	<i>Coefficient</i>
Aluminium .. ..	·000026	Concrete (av.) .. ..	·000012
Brass (av.) .. ..	·0000187	Steel (mild) .. ..	·000012
Copper .. ..	·000017	Brickwork (av.) .. ..	·000006
Glass .. ..	·000008	Stone .. ..	·000003
Invar .. ..	·0000009	to	·000009
Iron (cast) .. ..	·000011	Softwood (av.) with grain	·000005
Lead .. ..	·000029	Do. across grain ..	·000034
Tin .. ..	·00002	Hardwood (av.) with grain	·000004
Zinc .. ..	·000029	Do. across grain ..	·00005
Platinum .. ..	·000008		

From Table 17 it will be seen that mild steel and average concrete have identical coefficients. This fact is of great importance in reinforced concrete construction where steel is embedded in concrete for the purpose of taking tensile and shearing stresses. If the two materials had widely different coefficients the adhesion or grip between the two would be impaired by differential temperature movements.

A similar case, not so important from our point of view, but worth mention, is the identical coefficient of glass and platinum. In some chemical apparatus it is necessary to fuse a metal into a glass vessel for the purpose of forming electrodes. Platinum and glass may be combined, but if other metals were used the unequal contraction upon cooling would crack the glass.

## 2. EXPANSION AND CONTRACTION OF LIQUIDS.

The temperature movement of liquids is of course volumetric and its amount is in general very much greater than for solids. This is easy to understand for the molecules of a liquid are free to move relative to each other to a far greater extent, and for a given temperature rise a greater increase in vibration naturally occurs.

The thermal expansion and contraction of liquids has been seen in the liquid thermometer but a simple experiment with water will demonstrate better a further important point.

**EXPERIMENT 142.**—To show the expansion of a liquid.

Fit a long, thin glass tube into a bung, as in Fig. 302, and push the bung tightly into the neck of a small flask entirely full of water or other liquid. The liquid will rise some distance up the tube by displacement from the flask. Mark the level on the tube and then

apply heat suddenly to the flask by wrapping around it a cloth that has just been soaked in very hot water, watching the level carefully. It will be observed to fall slightly at first and then to rise steadily. We noted this momentary fall in level when dealing with the mercury thermometer but in the present instance it is much more marked. It is due to the fact that a small expansion of the flask itself first took place, so increasing its capacity, and the fall in level took place because the liquid had not yet commenced its expansion. It is more noticeable here than in the thermometer because the flask is much larger and of thicker glass than the thermometer bulb.

Upon further heating, the temperatures of the flask and the liquid are equalized and both continue to expand.

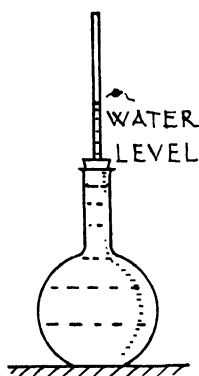


FIG. 302.—Temperature Movement of a Liquid.

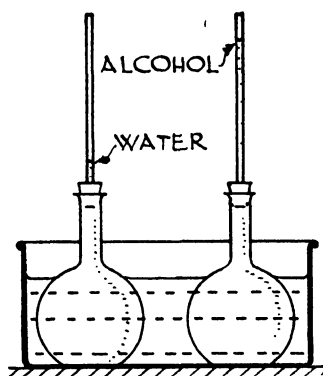


FIG. 303.—Comparison of Temperature Movement of Different Liquids.

The amount of expansion of the liquid we have just observed is thus an *apparent expansion* and not the actual or *real expansion*. The apparent expansion is always less than the real expansion, but as the expansion of a solid vessel is slight by comparison with that of the liquid we may, for our purpose, ignore the effect.

**EXPERIMENT 143.**—To compare the expansion of different liquids.

Fit up two identical flasks and tubes as in Experiment 142, filling one with water and the other with methylated spirit. See that the levels in the tubes are identical, then place both flasks in warm water. The spirit will show a much greater expansion than the water.

The coefficient of volumetric expansion for solids is almost exactly three times the coefficient of linear expansion. If required the coefficients given in Table 17 should therefore be multiplied by three. The coefficients of superficial expansion, although seldom required, can be obtained by doubling the linear coefficients.

TABLE 18.

COEFFICIENTS OF VOLUMETRIC EXPANSION (Real) OF LIQUIDS.  
(Below 40 deg. Cent.)

Substance	Coefficient
Water* .. .. .	·0002
Turpentine .. .. .	·001
Mercury .. .. .	·000181
Alcohol .. .. .	·0011

\* Varies considerably with temperature.

When dealing with solids we assumed with no great error that expansion was uniform over a long range of temperature. With liquids the expansion is far from uniform, and varies with different liquids, but water is the liquid with which we are most concerned.

EXPERIMENT 144.—To observe the temperature movement of water.

Fit up a small flask as in Experiment 142, but using coarse capillary or thermometer tubing. Arrange for the water level to be a few inches above the bung and stand the flask in a large beaker, packing it round with small ice. Melt the ice slowly with a low Bunsen flame and immediately it has all liquified mark the water level on the tube and watch it carefully.

It will be seen at first to fall slightly for a short time before commencing to rise. This is quite different from the fall noted in Experiment 142 for we have not heated the flask suddenly, although it is of course the apparent expansion that we observe.

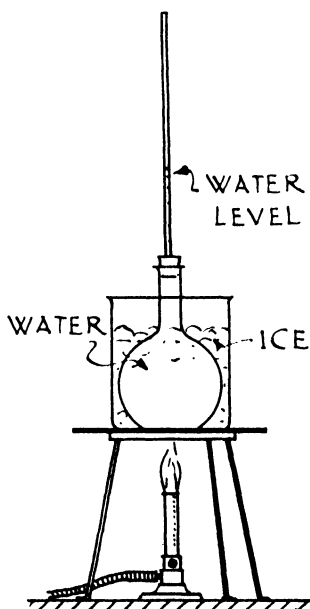


FIG. 304.—The Temperature Movement of Water.

We learn from this that the point at which water occupies a *minimum volume* is not at 0 deg. C. but slightly above this temperature, actually, as a more accurate experiment would show us, at 4 deg. C. As density increases with decrease in volume water is at its *maximum density* at this temperature. It will be remembered that water at its maximum density is the standard of density. Fig. 305 shows the behaviour of water (1 gram) when heated under atmospheric pressure from -10 deg. C. to 110 deg. C. including the contraction from 0 deg. C. to 4 deg. C.

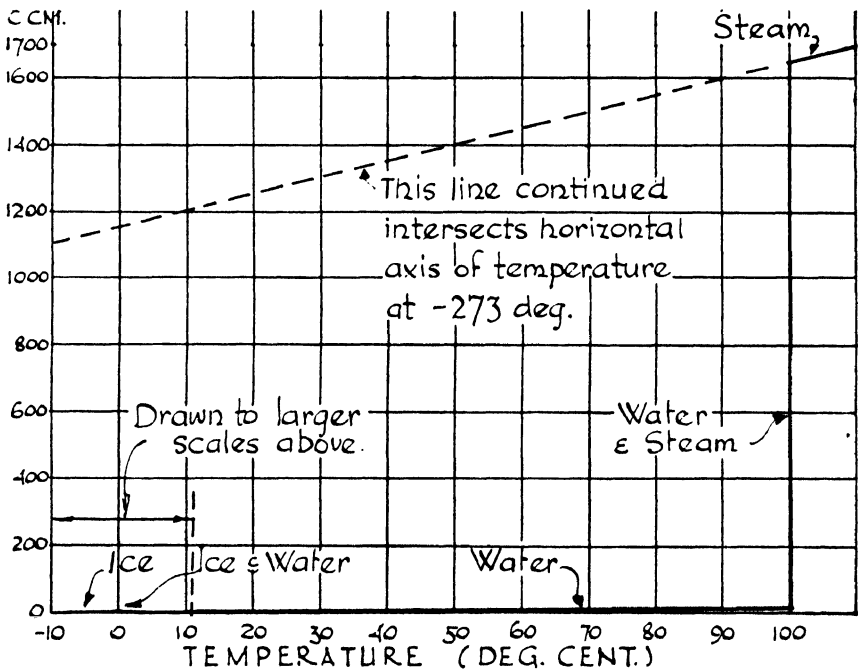
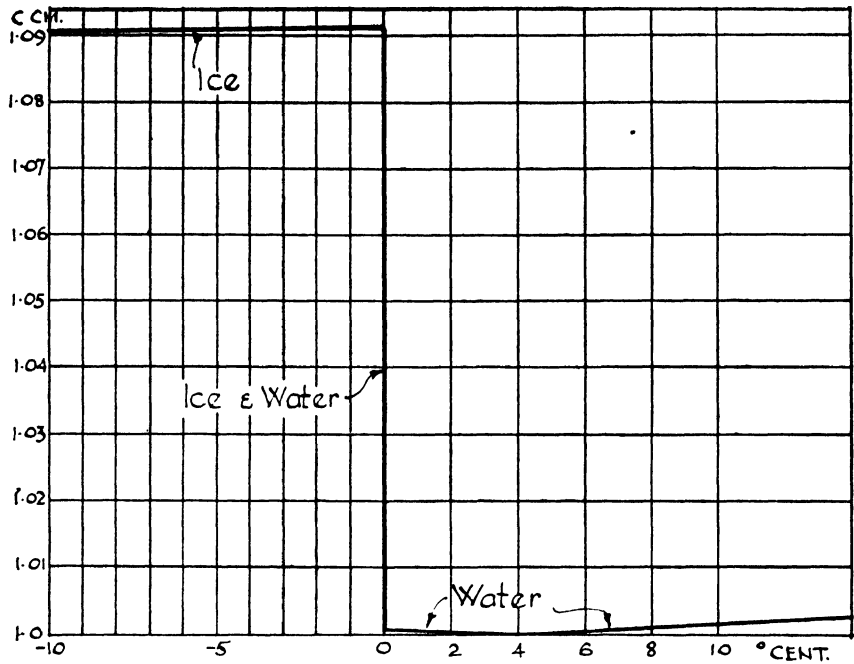


FIG. 305.—Graphs showing Volume of 1 gram of Water related to its Temperature.

The actual figures are :—

Volume of 1 gm. of ice	at	-10 deg. C.	=	1.0904 c.cm.
" " " " " "	"	0	"	= 1.0908 "
" " " " water	"	0	"	= 1.0001 "
" " " " " "	"	4	"	= 1.0 "
" " " " " "	"	50	"	= 1.012 "
" " " " " "	"	100	"	= 1.0433 "
" " " " steam	"	100	"	= 1650.0 "
" " " " " "	"	110	"	= 1690.0 "

### 3. EXPANSION AND CONTRACTION OF GASES.

As might be expected gases expand to a far greater extent even than liquids, and it can be proved that *all gases expand equally*, under identical conditions of pressure.

EXPERIMENT 145.—To demonstrate the expansion of air.

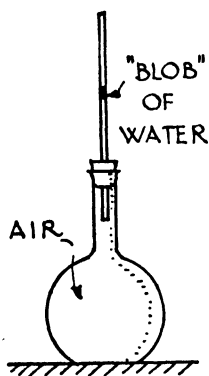


FIG. 306.—The Temperature Movement of Air.

Fit a long glass tube (not a capillary tube) to a small flask as in Fig. 306, making sure that the bung is a good fit. Now turn upside down and immerse the open end of the tube in a beaker of water, keeping the hands around the flask so as to warm it slightly. As the air in the flask becomes warm it expands sufficiently to force several bubbles out through the water. Now keeping the tube under water remove the hands except merely to hold the flask by its neck between finger and thumb. As the air cools again it contracts and a small quantity of water enters the tube. Remove the tube from the water and a "blob" of water will remain in the tube as shown.

Now on heating the flask the "blob" rises, and upon cooling it descends.

We know from our study of matter in Chapter I that gases always fill a containing vessel and exert pressure on the sides. If the gas is heated and escape is prevented, the pressure will clearly increase: consequently in any dealing with gases the temperature, volume and pressure are all involved.

Whilst it is not difficult to show experimentally the relation of temperature, volume and pressure of a gas it is not necessary for our purpose. We will therefore merely state this relationship.

Provided that the temperature remains constant, the product of the volume and pressure of any given mass of any gas is constant. This is known as *Boyle's Law* and is usually stated :—*At constant temperature the volume of a given mass of gas varies inversely as its pressure.* Thus if we maintain a constant temperature and halve the volume of a body of gas by compressing it the pressure is doubled, and so on.

Under constant pressure the coefficient of expansion (volumetric) of any gas is  $\cdot 00366$  or  $\frac{1}{273}$ . If we maintain a constant pressure, therefore, and raise the temperature through 1 degree centigrade the volume increases by  $\frac{1}{273}$  of its previous volume. Thus if we have 273 c.cm. of gas at 0 deg. C. and we raise it to 1 deg. C. its volume increases to 274 c.cm. ; if we raise it to 100 deg. C. its volume becomes 373 c.cm. If we cool it to  $-10$  deg. C. its volume is reduced to 263 c.cm., etc., etc. This is known as *Dalton's* or *Charles's Law*, usually stated :—*At constant pressure the volume of a given mass of gas increases by  $\frac{1}{273}$  of its volume at 0 deg. C. for every 1 deg. C. rise in temperature.*

Finally, maintaining the same volume, if we raise the temperature of a gas by 1 deg. C. its pressure is increased by  $\frac{1}{273}$  of its previous pressure. This is the *Law of Pressure*, stated :—*At constant volume the pressure of a given mass of gas increases by  $\frac{1}{273}$  of its pressure at 0 deg. C. for every 1 deg. C. rise in temperature.*

From these three laws we get the statement :—

$$\frac{PV}{T} = \text{a constant}$$

where P = Pressure.

V = Volume.

T = Temperature. (Absolute.)

#### 4. EFFECTS OF TEMPERATURE MOVEMENT.

We have just seen that the effect of a rise in temperature upon an enclosed volume of gas is to increase its pressure. The effect on the bounding surfaces is to produce a state of stress in the material and consequently a strain. When a boiler bursts it is usually because the internal pressure of steam produces a stress exceeding the ultimate stress for the steel.

Domestic and similar "boilers" used for low-pressure hot water supply and heating systems are not boilers in the strict sense of the word,

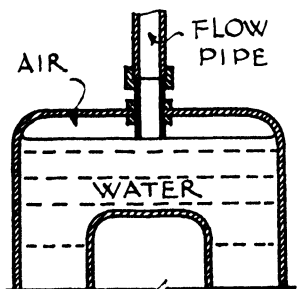


FIG. 307.—Entrapped Air in a Boiler.

for the water is not supposed to reach boiling point—if the system is suitably designed and installed and is functioning properly the water cannot boil—nevertheless they occasionally fail by bursting. This is usually because of entrapped air. If the boiler is not set perfectly level, or if the flow pipe is connected so as to protrude into the interior as in Fig. 307, or if its connection is on the side instead of the top of the boiler, a pocket of air is left when the system is filled. When, subsequently, the water is

heated it expands and compresses the air possibly to a dangerous degree. The alarming noises sometimes heard in such systems are due to such air escaping violently up the pipes.

The hot water in a low-pressure system rises to a level higher than that of the cold water in the feed cistern and must be accommodated by an "expansion" pipe carried up to a higher point. This pipe has an open end so that it also acts to ensure that the water in the system is not subjected to higher pressure than that of the atmosphere.

In high-pressure heating systems this pipe is sealed, or terminates in a sealed air chamber. The high pressure necessary for the proper working of the system is then produced by the expansion of the water, on heating, compressing this small volume of air.

**PRECAUTIONS NECESSARY ON ACCOUNT OF TEMPERATURE MOVEMENT.**—Some precautions that have to be taken because of temperature movement are well known.

The gap left between the ends of steel rails is necessary to accommodate the appreciable expansion which occurs as a result of an increase in temperature. Assuming 60-ft. long rails and a temperature variation of 40 deg. C. the movement is :— $0.000012 \times (\text{from Table 17}) \times 60 \times 12 \times 40 = .35\text{-in.}$  This is shared by both ends of each rail, but as the ends of adjacent rails come together this is the minimum gap necessary to prevent the rails from thrusting on to each other.

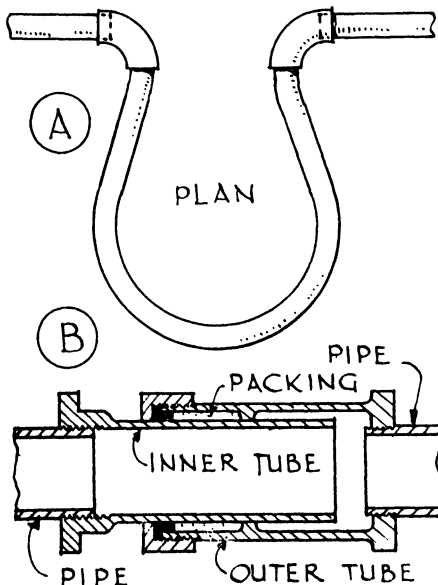


FIG. 308.—Precautions against Temperature Movement in Pipes.

The iron fire bars under boilers are subjected to very great temperature changes and must therefore be fitted loosely.

Iron castings must be carefully designed so that there are no sudden changes of direction, angles being well rounded and ribs incorporated for this purpose, otherwise cooling results in severe internal stresses which may result in fracture.

Hot water and steam pipes must be provided with means to accommodate temperature movement if laid in long, straight lengths. Loops or telescopic joints are used, as shown in Fig. 308.



The expansion of steel girder bridges is allowed for by mounting one end on steel rollers, whilst large roof trusses are often somewhat similarly arranged with the "free" ends supported on greased plates with slotted holes for the holding down bolts.

The concrete "cover" to the steelwork of a steel-framed building is provided not so much as protection against rusting as against extremes of temperature such as would occur in the event of a fire. Unprotected steelwork in a conflagration is notorious for its liability to bend and twist into fantastic forms, so usually increasing the damage by assisting collapse.

Sheet lead, copper and zinc, when used on "flat" roofs must be laid in sheets of comparatively small extent so as to limit the amount of movement of each sheet. The joints must also be of the roll or welt form so as to permit of this minimum movement without restraint. As a rule such sheets are rectangular, narrow in relation to their length, and fixed by nailing at one end only. Even so it is impossible to prevent entirely buckling due to expansion. The following experiment serves to demonstrate this buckling or waving.

**EXPERIMENT 146.**—To show the buckling of sheet lead due to fixing.

Fix a long glass tube about  $1\frac{1}{4}$ -in. in diameter to a slight fall as in Fig. 309 and arrange for steam to be admitted. Take a wood lath narrow enough to enter the tube and secure to it a thin strip of lead by pinning at both ends. The lead should be very thin to show the maximum movement and may be prepared by rolling out a strip of 3-lb. or 4-lb. lead. Slide the lath into the tube and then pass steam through. The lead will expand and lift from the lath in a series of waves.

Allow to cool and then repeat the experiment with one end of the lead strip free. This time the strip will merely slide upon the lath without buckling.

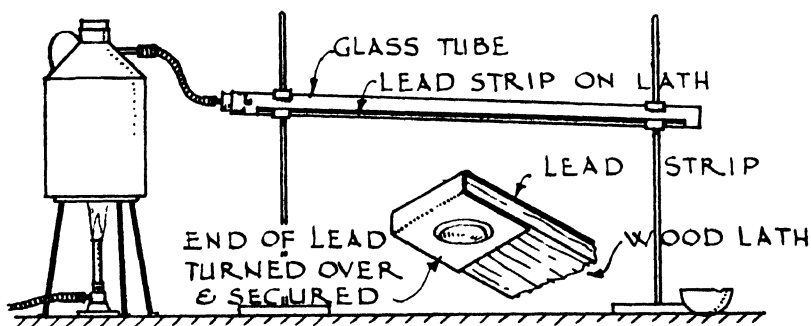


FIG. 309.—To show Buckling of Strip Lead due to End Fixing.

Sheet lead on pitched or vertical surfaces is subject to "creep," as also is vertically fixed lead piping such as rainwater downpipe. This is

due to the fact that lead is not an elastic material and cannot, upon cooling, contract to its exact former length on account of its own weight. It therefore lengthens slightly at each alternation of temperature and ultimately draws out thin at the upper end where it is fixed. In the case of sheet lead this causes the nails to tear through the edge of the sheet, and for this reason it is better to tuck the top of the sheet through the boarding and nail on the underside, so providing a continuous bearing. This does not prevent creep but reduces risk of complete failure. In the case of lead pipes each length is supported individually at the socket by a block joint or stirrup, so minimizing the amount of creep.

**EXPERIMENT 147.**—To show the creeping action of lead.

The apparatus shown in Fig. 310 comprises a wide glass tube fixed vertically and with an arrangement for passing steam into it. Through the tube passes a length of lead wire fixed at the top to a screw and at the bottom to a pointer pivoted at one end, and with a small weight to keep the wire taut. Observe the position of the pointer on the scale before heating, then pass steam into the tube. As the lead wire expands the pointer moves down the scale, and upon cooling to its original temperature it moves up again but comes to rest some distance below its original position.

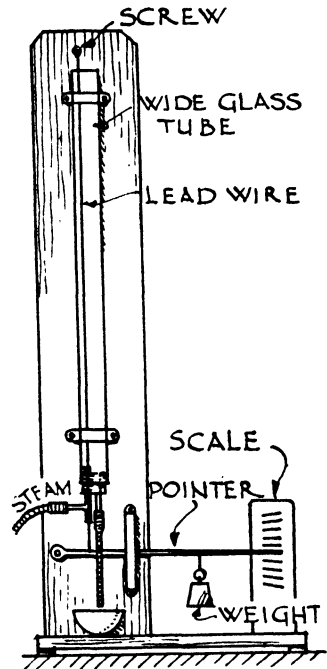


FIG. 310.—To show Creeping of Lead Wire.

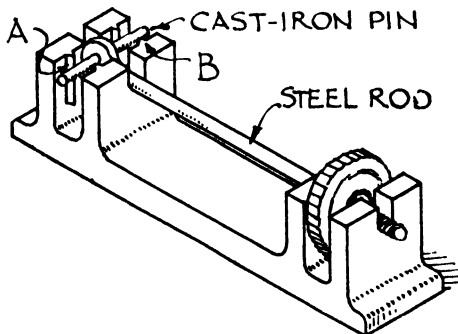


FIG. 311.—Stress induced by Restraint of Temperature Movement.

**FORCE EXERTED BY RESTRAINED TEMPERATURE MOVEMENT.**—In Experiment 146 the restraint imposed by fixing both ends of the lead strip caused buckling. If instead of lead a rod of steel or other rigid material had been used it will be appreciated that considerable force would be exerted at the extremities. This may be demonstrated by the apparatus shown in Fig. 311.

**EXPERIMENT 148.**—To show the effect of restraining temperature movement.

A steel rod has an eye at one end and is threaded for a screw nut at the other. The rod is placed in position in the apparatus as shown, a cast iron pin passed through the eye, and the nut withdrawn as far as it will go. This has the effect of causing the pin to bear on the ribs marked A. Now with a Bunsen flame heat the central portion of the rod and the rod will attempt to expand but is prevented from doing so by the fixity at the ends. Being stout and rigid it cannot buckle and very soon the stress induced in the iron pin will cause it to fracture suddenly by a combination of shear and bending.

Whilst the rod is still hot pass a fresh pin through the eye and tighten the rod by screwing the nut in the opposite direction, so causing the pin to bear on the ribs B. Upon cooling the contraction of the rod gradually stresses the pin until it snaps like the first one.

**APPLICATIONS OF THE FORCE OF TEMPERATURE MOVEMENT.**—A thermostat is a contrivance which automatically operates light mechanism for the purpose of regulating dampers, taps, etc. It is used in ovens, water circulations, etc., but one of its commonest uses in connection with Building is for controlling the mixture of hot and cold air in plenum and air conditioning installations. In its simplest form it comprises a solid metal rod within a sleeve or casing, fixed to it at one end and free to move at the other, the expansion of the rod upon being heated applying pressure to some part of the mechanism being operated.

In rivetting steelwork the rivets are driven, and the rivet heads formed, at white heat. Upon cooling the rivet contracts in its length and so grips the plates tightly together with great force. The strength of a riveted joint is thus greater than that of a similar bolted joint.

Steel pillar caps and bases have supplanted cast iron construction owing to the ease with which they can be built up of steel angles, plates, etc. For round steel columns however this type of cap and base cannot be used. This type of pillar usually carries heavy loads and the problem is to fix a cap or base so that it shall be as nearly as possible "monolithic" with the pillar shaft, so as to transmit the loads efficiently. Such caps and bases are formed of a square slab of solid steel 3-in. or more in thickness, and they are drilled to receive the round shaft and shrunk on to it by being driven on hot and then allowed to cool and so exert a tremendous grip.

Circular brickwork kilns, retorts, stacks, etc., are subject to excessive temperature movement owing to the great variations of temperature. Brickwork under such conditions is subject to creep. Upon being heated it expands outwards in horizontal planes by sliding on the bed joints, but upon cooling its own weight together with the fact that it is not monolithic prevents its reverting to its original position. Such kilns, etc. are therefore bound at intervals of a few feet with stout wrought iron or steel bands or hoops. These, being continuous, are capable of contracting to their former diameters and in doing so they serve to pull back the brickwork.

The lower portion of a tall brickwork chimney stack is invariably lined with firebrick on account of the extremely high temperature of the escaping gases. The lining usually takes the form of a half-brick wall built of firebricks which must not be bonded into the brickwork of the stack itself. If this were done the vertical movement of the lining would snap off any header bonded in. Even the capping of the lining must be entirely dissociated from the stack.

## 5. TEMPERATURE MOVEMENT RELATED TO STRAIN AND MOISTURE MOVEMENT.

In Experiment 148 the prevention of temperature movement resulted in stress being produced in the steel rod—to such an extent as to strain and ultimately fracture the pin.

The expansion or contraction due to temperature change is clearly related to elongation or shortening due to loading, and to that due to gain or loss of moisture ; in fact all three types of movement are inter-related.

TEMPERATURE MOVEMENT AND STRAIN.—If a metal rod is heated it expands or increases in length. If a similar rod is subjected to a tensile force it suffers a similar increase in length, a strain. The same amount of elongation may thus be produced either by temperature change or by applied force, and if the temperature elongation is prevented, the stress produced is clearly equal to that which results in the strain. To put it another way, we may imagine the rod pushed back to its former length by compressive force applied at the ends ; the force necessary to do this is equal to the force exerted by the rod by prevention of its temperature expansion. The stresses induced by this restraint are known as *temperature stresses* and may be additional to the stresses resulting from the loading of the member or structure. Temperature stresses have to be allowed for in the designing of some structures, in other cases where they are known to occur, but not to a great extent, the factor of safety takes care of them.

**EXAMPLE.**—A wrought iron hot water pipe runs in a straight length for a distance of 50-ft. Its normal temperature of 15 deg. C. is raised to 95 deg. C. when the system is in operation. What stress would occur in the pipe if expansion were restrained? Coefficient of linear expansion = .0000114. Modulus of elasticity = 12,000 tons per sq. in.

$$\text{Coeff. of E} = \frac{\text{Expansion}}{\text{Original length} \times \text{temperature rise}}$$

Therefore

$$\begin{aligned}\text{Expansion} &= \text{Coeff. of E} \times \text{original length} \times \text{temperature rise} \\ &= .0000114 \times (50 \times 12\text{-in.}) \times (95 - 15) \\ &= .0000114 \times 600 \times 80 \\ &= .5472\text{-in.}\end{aligned}$$

$$\text{Total strain} = \text{expansion} = .5472\text{-in.}$$

$$\text{Therefore strain} = \frac{.5472}{600} = \frac{\text{Stress}}{E}$$

$$\text{Therefore stress} = \frac{.5472}{600} \times 12,000 = \underline{10.95 \text{ tons per sq. in. compression.}}$$

Needless to say the pipe would buckle badly.

In some types of structure, notably reinforced concrete arched bridges of long span and slender proportions, the stresses produced by temperature changes may be greater than those due to the normal loading.

In the traditional type of building any temperature movement is satisfactorily taken care of by distribution amongst many mortar joints, especially where lime mortars are used. With the increasing use of Portland cements, however, joints are less yielding and there are many cases in which temperature movement may constitute a serious problem if there is restraint. Straight walls which are restrained at the extremities frequently become stressed sufficiently to cause partial failure, especially parapet walls, balustrading, etc., which may have a very great unbroken length.

With increasing use of concrete in large buildings the necessity to make provision in the construction for thermal movement has become very real, especially where, for instance, an extensive roof slab is used in conjunction with brick or stone walling. Brick parapet walls to such roofs have been known to be pushed outwards by expansion of the roof slab. In a framed building the probability of trouble is less as the stresses are distributed amongst the members of the frame.

The temperature stress in a member which is restrained depends, temperature range and length being equal, upon the value of E for the material. Dense materials and rigid construction are thus subject to higher temperature stresses.

Stresses occur due to differential temperature movement where different materials are used in conjunction, but are normally not excessive.

Only as a rule under abnormal circumstances such as in a fire do they become serious.

**MOISTURE MOVEMENT AND STRAIN.** Strictly speaking consideration of this does not belong to the present chapter, but as there are instances in which temperature and moisture stresses may both be produced, its significance will be touched upon.

The failure, by splitting and buckling, of restrained woodwork in panels, etc. is well known, but it is perhaps not so much realised that other gel materials are similarly stressed when moisture movement is restrained. Monolithic concrete work is notorious for drying shrinkage, although the greater part of it occurs during initial setting. Nevertheless considerable moisture movement does occur subsequently during fluctuations of moisture content due to the maintaining of equilibrium with varying atmospheric conditions. At whatever stage it occurs it invariably stresses the material, owing to restraint, to the point of cracking unless precautions are taken to distribute the stress by special reinforcement or by "plumming." These remarks apply also, perhaps to a greater extent, to cement and similar renderings, in which the resulting tensile stresses produce cracks and shear stresses result in failure of bond to the backing.

With most porous building materials such as brick, stone, concrete, etc. the immediate effect of a temperature rise is usually to produce drying shrinkage, thermal expansion only showing after drying out has reached a certain point.

Differential moisture movement in a composite material results in stresses, quite apart from restraint of the material as a whole, and this usually occurs when materials of different densities are used in conjunction.

**TEMPERATURE AND MOISTURE MOVEMENT.**—Perhaps the most notable instance of simultaneous moisture and temperature movements is the enamelled fireclay brick. The glaze is an extremely thin coating of glass, applied as a rule only to one face and one end. The beds and other surfaces of the brick are therefore free to absorb moisture from the backing of brickwork, earth, etc., or sometimes rain from the back of a 9-in. parapet wall. This results in a certain moisture expansion which the glaze, being impervious, cannot share. This does not normally produce ill effects but upon an appreciable rise in temperature we get moisture shrinkage of the brick at the same time as temperature expansion of the glaze—two opposite movements which in many instances results in loss of bond between the two and causes the glaze to crack and even peel from the brick.

Enamelled tiles are affected similarly, the tile itself being porous whilst the glaze is non-porous, but these are not so much used externally.

**Exercises.**

1. A steel girder bridge is 150-ft. span and is fixed at one end only. Calculate its increase in length under a rise in temperature from 10 deg. C. to 35 deg. C.  
(Ans. .54-in.)
2. A monolithic concrete boundary wall is 300-ft. long. If it expands in length .864-in. for a temperature rise of 20 deg. C. what is the coefficient of linear expansion for the concrete ?  
(Ans. .000012.)
3. Assuming no alteration in pressure find the volume at  $-20$  deg. C. of air which has a volume of 70 c.ft. at 15 deg. C. (Temperatures must be converted to "absolute" temperatures by adding 273 deg.)  
(Ans. 61.4 c.ft.)
4. A steel rail 60-ft. long is fixed with no allowance for expansion and its temperature increases by 70 deg. C. Calculate the resulting stress.  
(Ans. 11.44 tons per sq. in.)

## LATENT HEAT

1. *Change of State.*
2. *Solders.*

## 1. CHANGE OF STATE.

One of the effects of heat upon a substance, as we have seen, is to raise its temperature. When this occurs we refer to it as *sensible* heat, or heat which affects our sense of feeling. When the application of heat does not produce a rise of temperature (when the substance changes its state) the heat absorbed is called *latent* heat, *i.e.* hidden heat or heat which cannot be felt. Changes of state are :—

- (a) Melting, liquifaction or fusion. (A change from solid to liquid.)
- (b) Setting, solidification or freezing. (Liquid to solid.)
- (c) Vaporization, *i.e.* evaporation and boiling. (Liquid to gas.)
- (d) Condensation. (Gas to liquid.) Also
- (e) Solution. (Solid to liquid.) And
- (f) Crystallization (from solution). (Liquid to solid.)

In all these changes of state latent heat is involved ; in (a), (c) and (e) it is absorbed (without rise of temperature), and in (b), (d) and (f) it is given up (without fall of temperature).

**Melting.**—The melting of a solid takes place because the heat motion of its molecules is increased, they move further apart, and in doing so their inter-molecular force is sufficiently reduced to cause them to lose their relative fixity of position.

## EXPERIMENT 149.

Place in a flask some crushed ice, cover it with cold water, and fit a two-hole bung through one

hole of which a Centigrade thermometer is passed and through the other a short bent tube. The thermometer bulb should be just below the surface of the mixture.

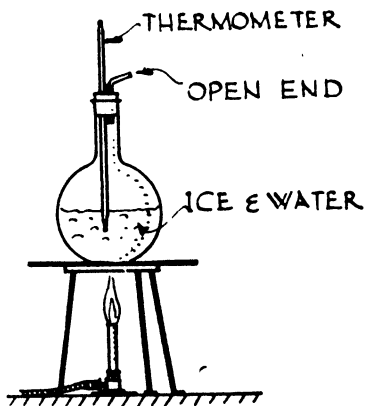


FIG. 312.—“ Absorption ” of Latent Heat of Melting.



Shake the flask slightly and then let it stand. The thermometer goes down to about 0 deg. C. and then remains constant.

Now place the flask on a tripod and heat very gently with a Bunsen (Fig. 312). The temperature does not rise whilst any ice remains unmelted, *although heat is being applied all the time*. The heat is being absorbed in melting the ice into water, and the temperature indicated by the thermometer during melting is called the *melting point* of the ice.

It can be shown by accurate experiment (which need not concern us here) that for every gram of ice at 0 deg. C. converted into water at 0 deg. C. eighty calories are absorbed. This is called the *latent heat of fusion of ice*. The latent heat of fusion of substances varies; for paraffin wax it is 35 calories, for sulphur 9 calories, etc.

**EXPERIMENT 150.**—To find, approximately, the latent heat of fusion of water.

Take the apparatus used in experiment 149 and place it away from draughts of air. Place some *dry* ice (in small lumps) into the flask and put it over the Bunsen flame, taking care not to alter the flame during the experiment.

Note the exact time: 1, when the flask is placed over the flame, and 2, when the ice has just melted, and 3, when the water just commences to boil.

The difference in time between 1 and 2, and between 2 and 3, will be found to be in the proportion of about 4 : 5. The heat has been applied at an almost constant rate, and we know that to raise 1 gm. of water from 0 deg. C. to 100 deg. C. 100 calories are required, therefore to melt 1 gm. of ice at 0 deg. C. to water at 0 deg. C.  $\frac{4}{5} \times 100 = 80$  calories are needed.

**MELTING POINTS.**—Most substances have, like ice, a definite melting point; they change from solid to liquid abruptly at a definite temperature, and as it is unusual for any two substances to have identical melting points this fact is important in enabling substances to be identified.

A few substances, for example glass, sealing wax, pitch, wrought iron, solder, have no definite melting point. Instead, they have an intermediate viscous stage, and advantage is usually taken of the fact in working in the material; wrought iron is rolled and welded, glass is fused together or blown, etc., whilst in this semi-solid state.

To determine the melting point of a substance the method adopted depends upon the manner in which it melts and upon the temperatures involved. For a substance with a definite melting point less than 100 deg. C. the following method may be used.

**EXPERIMENT 151.**—To determine the melting point of paraffin wax.

Melt a little wax and dip into it the bulb of a thermometer, then withdraw it and allow to cool. The bulb is then covered with a thin coating of solid wax. Heat some water in a beaker up to about 45 deg. C., then turn the Bunsen to a low flame, continuing the

heating gently. At this point introduce the thermometer into the water, stirring gently and watching for the wax coating to melt and so become transparent.

The mean of a number of experimental results gives the melting point as approximately 53 deg. C.

This method gives only an approximate result and is obviously unsuited to all substances, especially those having no definite melting point. More accurate methods are described under *Setting*.

**MELTING AND CHANGE OF VOLUME.**—Although solids expand upon being heated they do not all show a continued increase in volume after melting. A few, including cast iron and water, contract upon melting and expand upon setting. Unmelted iron therefore floats in the melt just as ice floats in water because its density is lower.

This property of iron is noticeable in castings. If, say, a cast iron rain water hopper head is inspected and compared with a similar head in cast lead, the iron casting will be seen to be “sharp” with perfect arrises, etc., whereas the lead casting is “soft” by comparison.

**EXPERIMENT 152.**—To show the contraction of ice upon melting.

Fill a small flask with a mixture of ice and water, fit a bung through which passes a long glass tube and mark on the tube the level of the water. Now heat gently so as to melt some of the ice. The water level in the tube is seen to fall steadily until the ice has melted.

**EFFECT OF PRESSURE UPON MELTING POINT.**—It can be shown that a substance which contracts upon melting has its melting point lowered by being subjected to pressure, whilst the melting point of a substance which expands upon melting is raised. This phenomenon may be shown quite easily in the case of water. If two pieces of ice are pressed together they become joined. The pressure lowers the

melting point over the area of contact and causes the surfaces to melt, release of the pressure then enabling the water thus formed to freeze again. This process is called *re-gelation*. The “slipperiness” of a surface of ice is proverbial; this is due not merely to its smoothness

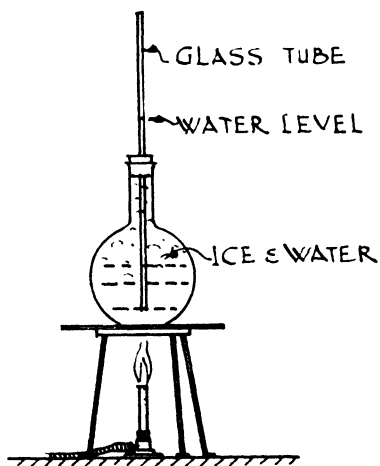


FIG. 313.—Contraction of Ice upon being Melted.

for it is no smoother than many other materials, but to the fact that the pressure from our soles momentarily melts the ice at the surface and so produces a film of water which acts as a lubricant.

**EXPERIMENT 153.**—To demonstrate re-gelation.

Make a small block of ice about  $1\frac{1}{2}$ -in. square and 3-in. long. Support it as a beam on two bricks and hang a 1-lb. weight centrally by means of a thin wire. The wire slowly passes completely through the block and, with the weight, falls to the ground but the block is found to be still whole (Fig. 314).

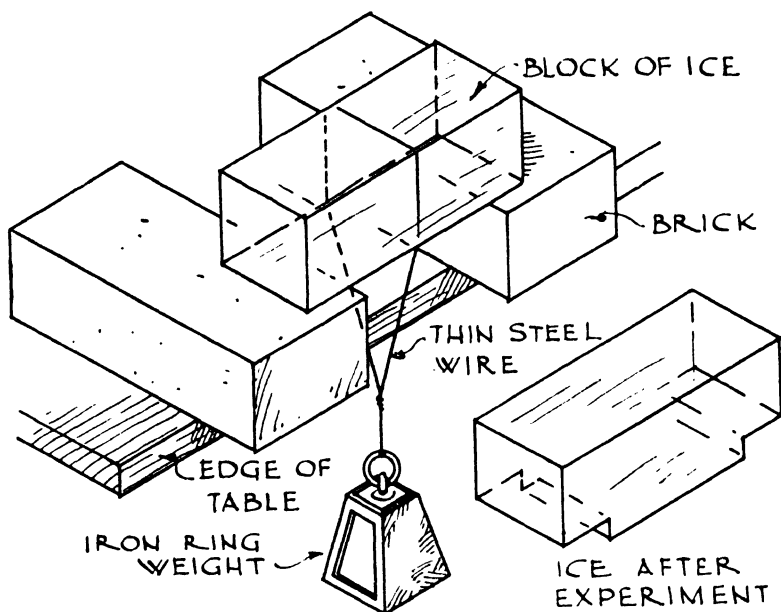


FIG. 314.—Experiment to Show Re-gelation.

**Setting.**—The setting or freezing of a liquid is the reverse of the melting of a solid. The reduction in temperature reduces heat motion with a consequent increase in the force of cohesion.

A substance which has a definite melting point also has a definite setting point, in fact the two are identical. The melting point may therefore be found by finding the setting point, this being easier experimentally since it is found during the cooling of the substance, and the thermometer bulb can be kept in it during the whole process.

The latent heat of setting of a substance is, of course, identical with that of fusion. The heat absorbed by the substance during melting is given up again during setting. Thus, when 1 gm. of water at 0 deg. C. is converted into ice at the same temperature 80 calories are yielded up, and whilst the change is taking place there is no fall of temperature.

**EXPERIMENT 154.**—To determine the setting point of paraffin wax.

Melt some wax as in Experiment 151 and dip the bulb of the thermometer into it. When the temperature is 60 deg. C. or thereabouts remove the thermometer and clamp it in a stand away from draughts. The bulb is covered with a thin transparent film of molten wax which becomes opaque upon setting. Carefully watch for this to occur and note the thermometer reading.

Repeat several times and the mean result will be found to be about 53 deg. C. as for the melting point.

A more accurate method is to record the temperatures of the wax during slow cooling.

**EXPERIMENT 155.**—To determine the setting (and melting) point of paraffin wax from a cooling curve.

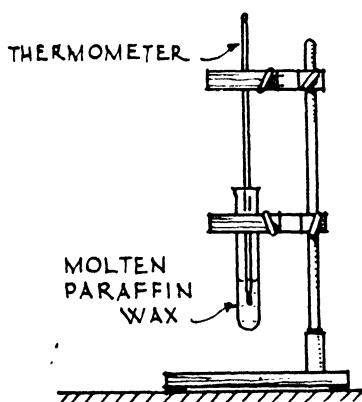


FIG. 315.—Setting Point of Paraffin Wax.

Melt the wax in a test tube to a point well over its melting point but within the range of the thermometer. Clamp it in a stand with a thermometer as in Fig. 315 and take readings of temperature at regular intervals, say every minute, until after setting has taken place. Plot the results as a graph (Fig. 316) and from the curve it will be seen that the fall in temperature is fairly steady until about 53 deg. C., when the latent heat of setting is given up, resulting in a halt for a short time, cooling off being then resumed.

#### CHANGE OF VOLUME UPON SETTING.

—The change of volume upon setting is the reverse of that which takes place upon melting. Thus water expands upon freezing—to the extent of about 9 per cent.—and this results in tensile stresses in the walls of water pipes, etc., which sometimes result in fracture, although the damage usually becomes apparent only after melting during a thaw.

If a small bottle with a screw cap be filled with water and frozen it will fracture by internal expansion.

We have already noted that cast iron expands upon freezing, but most substances contract, and this is sometimes a disadvantage, as in the case of lead when used for jointing purposes. In such cases, as in the fixing of iron to stonework, the lead is run into the joint in a molten condition and then caulked or consolidated by ramming at the time of setting.

**EFFECT OF IMPURITIES UPON SETTING POINT.**—The setting and melting point of a substance is altered by the presence of impurities. This fact may enable its purity to be tested.

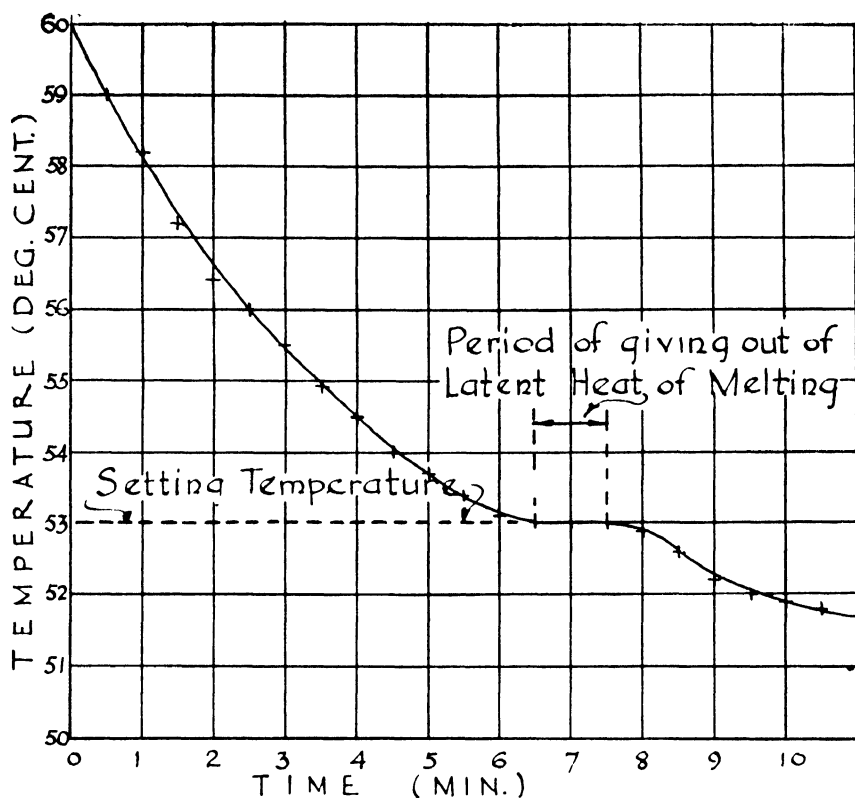


FIG. 316.—Cooling Curve for Paraffin Wax.

**EXPERIMENT 156.**—To show the effect of adding salt to ice.

Stand a test tube containing water upright in a beaker and pack the space surrounding the tube with a mixture of crushed ice and common salt. After a time, when the ice might be expected to have melted, it will be found that this has not taken place although the water in the test tube has frozen.

Put a solution of common salt and water into a test tube, fit a bung through which passes a thermometer and place it in the beaker surrounded by the ice-salt mixture. Agitate the beaker until the solution freezes and then note the temperature. It will be considerably below 0 deg. C., depending upon the strength of solution.

**Evaporation.**—At the free surface of a liquid the molecules of liquid are not restrained to the same extent as those at greater depth and their vibration enables them to leave the liquid (to jump out as it were) and mix with the more loosely spaced molecules of air or other gas which is in contact with it. If the liquid surface is not in contact with a gas (when the liquid is in a vacuum) it is easier still for these molecules to detach themselves and enter the space above. The application of heat

increases the vibration or heat motion of the liquid molecules and so speeds up the process of evaporation.

It should be noted that evaporation can take place only at the free surface of a liquid—not from the interior—and that it proceeds at any temperature, being more rapid the higher the temperature.

**LATENT HEAT OF VAPORIZATION.**—As evaporation cannot take place without heat motion it will be clear that heat is lost by a liquid from which evaporation is going on, also that the remainder of the liquid will then absorb heat from its surroundings to maintain temperature equilibrium. These surroundings will thus be cooled as a result of the evaporation.

**EXPERIMENT 157.**—To show cooling produced by evaporation.

Pour a few drops of liquid ether on to the back of the hand and wave the hand to and fro to assist evaporation. The ether disappears very quickly and produces a sensation of intense cold, heat being taken from the hand to make up for that lost in the evaporation.

**EXPERIMENT 158.**—To show cooling produced by evaporation.

Pour a few drops of water on to a match box or small piece of wood, place on it a thin watch glass containing liquid ether and evaporate the ether rapidly by blowing on it through a tube. The water will freeze and cause the glass to adhere to the wood.

The significance of this in a building is that walls, etc. that are damp through faulty construction, unsuitable materials, or from any other cause are always cold and so produce conditions of discomfort. For the same reason a cold and damp climate is less comfortable and healthy than one that is cold but dry.

The porous earthenware butter and milk coolers are a more everyday example in which the cooling effect of evaporation is utilized. To be effective they must be saturated with water and placed in a current of air.

**Boiling.**—Boiling is also vaporization but, unlike evaporation, it takes place throughout the mass of a liquid, and under given conditions at a definite temperature only.

**EXPERIMENT 159.**—To determine the boiling point of water.

Half fill with water the flask used in Experiment 149, insert the thermometer so that its bulb is below the surface, and heat with a Bunsen. Small bubbles will form on the sides and base of the flask and will soon become detached and rise to the surface. These are bubbles of gas held previously in solution by the water, and are not to be confused with steam.

Later, larger bubbles form rapidly in the body of the water and rise violently to the surface. This process continues with some commotion (unless some small pieces of metal or glass have been placed inside the flask), the steam being invisible inside but becoming apparent as a cloud of condensed steam on issuing into the cooler air.

The temperature as recorded by the thermometer has been rising steadily until boiling commences and it now stands at about 100 deg. C., but does not rise further *although heat is still being applied*. The heat is being absorbed in converting the water into steam *at the same temperature*. To verify this, raise the thermometer until its bulb is just out of contact with the water, when it will still record the same temperature, this being the *boiling point* of the water.

The latent heat of vaporization of water is 537 calories per gm. That is to say, for each gm. of water at 100 deg. C. turned into steam at the *same* temperature 537 calories are needed. Similarly the latent heat of vaporization of alcohol is 202, turpentine 74, etc., etc.

**EXPERIMENT 160.**—To find, approximately, the latent heat of vaporization of water.

This is really a continuation of Experiment 150. Place ice and water in the flask and heat with a constant flame, noting the exact time (1) when the ice has just melted, (2) when the water commences to boil, (3) when the water has completely boiled away. The difference in time between (1) and (2), (2) and (3), will be roughly in the proportion 1 : 5.33. Now, as heat has been applied at fairly constant rate it takes about 5.33 times as much heat to vaporize the water as to raise it from 0 deg. C. to boiling point, *i.e.*  $5.33 \times 100 = 533$  calories.

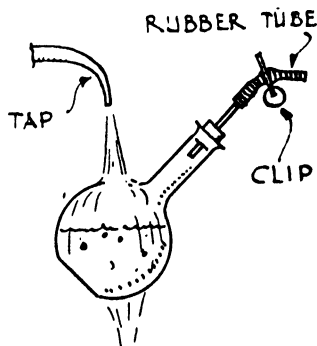
Accurate experiment shows it to be 537 calories as stated earlier.

**VAPORIZATION AND CHANGE OF VOLUME.**—As might be expected from consideration of the respective structures of liquids and gases the change from one to the other is accompanied by great expansion. The volume of water is increased about 1,650 times as it is turned into steam, as was shown in the graph, Fig. 305, and if this expansion is restrained high pressure is developed.

**EFFECT OF PRESSURE UPON BOILING POINT.**—A liquid boils at different temperatures according to the air pressure on the free surface. Under a lower pressure than standard, water boils at less than 100 deg. C., and under higher pressures it boils at temperatures higher than this.

**EXPERIMENT 161.**—To show boiling under reduced pressure.

Fit a flask, preferably a round bottomed one, with a bung and short glass tube fitted with a short rubber tube. Half fill with water and boil so that steam issues in quantity from the rubber tube. When this occurs



**FIG. 317.**—Effect of Reduction in Pressure upon Boiling Point.

close the tube with a pinchcock and *at the same time* remove the Bunsen.

The water will be seen to continue to boil for some time afterwards. Now pour cold water over the flask. This cools it and results in the steam being re-converted into water so leaving a much reduced pressure inside the flask. The water re-commences to boil, and continued cooling prolongs the period of boiling so that the flask may be supported on the palm of the hand whilst still boiling furiously.

Conversely, the rise of boiling point with increase of pressure may be shown, and this is significant in connection with hot water heating systems. In a low-pressure system the water is kept at atmospheric pressure by means of the open-ended expansion pipe. It thus cannot become hotter than about 100 deg. C. even if it should inadvertently boil.

In cases where higher temperatures than this are desired, such as when smaller bore pipes are used, the system is sealed so as to leave only a limited volume of air enclosed above the water. The expansion of the water upon being heated then compresses this air and applies an increased pressure to the water so that the water does not boil so readily. In this way higher temperatures are obtained whilst retaining the advantages of hot water as distinct from steam in the circulation. At a pressure of 200 lb. per sq. in. the boiling point becomes 194 deg. C. and much higher temperatures than this are possible. The chief reason for the comparative decline in popularity of these high pressure systems is that occasional understanding attention is necessary in the matter of adjusting the air chamber so as to avoid excessive temperatures. Such temperatures tend to scorch dust particles and produce an objectionable atmosphere, besides being a possible source of danger when in contact with woodwork or other combustible material.

**EFFECT OF IMPURITIES UPON BOILING POINT.**—As with the melting point the presence of impurities affects the boiling point, and this fact affords a means of detection.

**EXPERIMENT 162.**—The effect of salt upon the boiling point of water.

Use the apparatus shown in Fig. 312. First boil plain water and record the boiling point under the conditions of the experiment. Then add a little common salt and repeat, when the temperature recorded will be slightly higher. Add still more salt, and the boiling point will rise again.

Raise the thermometer so that it does not dip into the liquid. The temperature immediately falls to the original temperature of the plain water, showing that the vapour is steam only.

**Condensation.**—Condensation is the reverse of vaporization and is thus accompanied by the yielding up of the latent heat of vaporization—viz. 537 calories per gm. in the case of water. For any substance the



temperature at which condensation takes place is that at which boiling takes place. Boiling point and condensation point are thus identical, as are melting and setting points.

**EXPERIMENT 163.**—To note the effect of the condensation of steam.

Place equal quantities of cold water, say 100 gm., into two beakers. Take its temperature, say 14 deg. C. To one of them add 100 gm. of boiling water, stir and take the final temperature (about 55 deg.). Into the other introduce the outlet of a rubber tube leading from a boiler in which 100 gm. of water is being boiled. As the steam bubbles through the water stir and read the temperature from time to time. The water will reach boiling point in a few minutes, long before the water in the boiler has boiled away.

In addition to the sensible heat from the steam (which is the same as that from the boiling water added to the first beaker) the latent heat absorbed by the steam in its conversion from water is now yielded up upon again being changed into water.

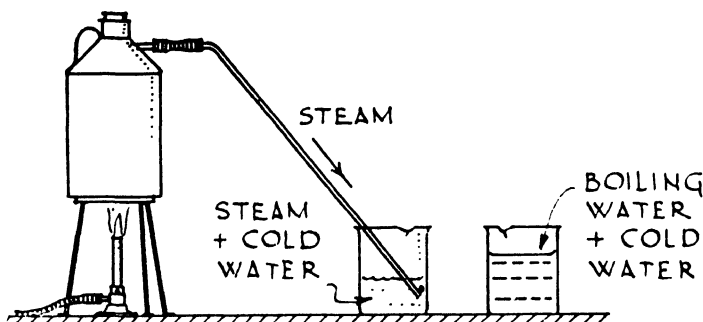


FIG. 318.—Yielding of Latent Heat upon Condensation.

This is the principle of steam heating systems. The water in the boiler is boiled and the steam transferred via pipes to radiators in which it condenses, so giving up its latent heat of 537 calories per gm. (equivalent to 966 B.Th.U. per lb. of water) and it is this which is mainly responsible for maintaining the high temperature of the radiators. The condense water finds its way back to the boiler along the pipes which are arranged to facilitate this—*i.e.* with no horizontal portions or reverse falls.

The same principle is sometimes utilized in hot water supply systems, especially in scattered types of buildings such as institutions, for communal installations, and in cases where waste steam is available. For such cases the steam is passed through a coil or cylinder inside a "calorifier" where it condenses and gives up its heat to the water without actually coming into contact with it. Fig. 319 shows two types of calorifier.

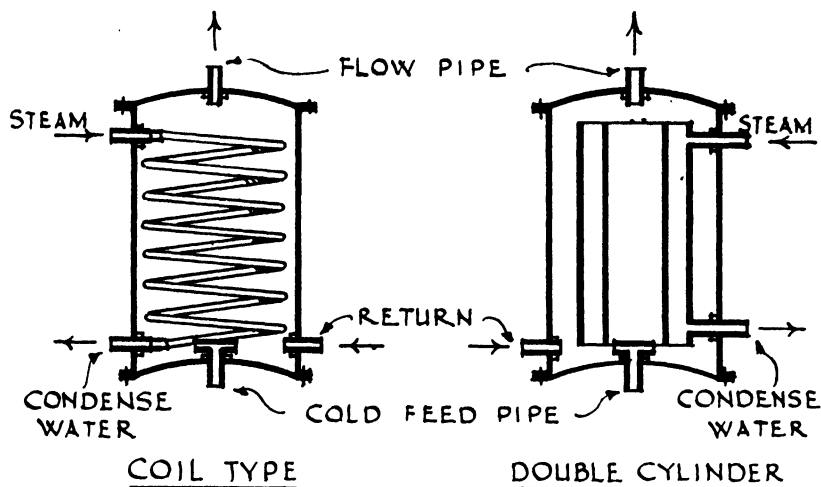


FIG. 319.—Types of Calorifier.

The latent heat of vaporization (and condensation) of water is very much higher than that of any other liquid (it will be remembered that its specific heat is also the highest) and this is another reason for the pre-eminence of water as the agent in heating systems.

### Solution.

EXPERIMENT 164.—To show the latent heat of solution.

Take a large beaker two-thirds full of cold water and a narrow test tube containing two inches or so of water. Add ammonium nitrate slowly to the beaker, stirring vigorously with the test tube. Keep up the process, constantly adding the nitrate, and after a time the water in the test tube will be frozen.

The dissolving of the ammonium nitrate absorbs heat from its immediate surroundings including the test tube.

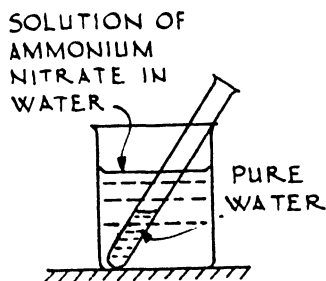


FIG. 320.—“Absorption” of Latent Heat of Solution.

**Crystallization.**—The latent heat taken up by substances upon solution is given up again upon re-crystallization. The following experiment best shows this because of the extremely rapid formation of crystals.

EXPERIMENT 165.—To show the latent heat of crystallization.

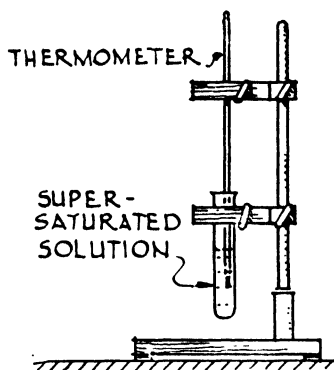


FIG. 321.—Yielding of Latent Heat upon Crystallization.

Dissolve sodium thio-sulphate (sometimes called "hypo-sulphite") in a little hot water in a test tube until a saturated solution is obtained. If any excess of thio-sulphate remains, heat the solution until it passes into solution. Then clamp the tube in a stand with a thermometer in it and leave undisturbed until it is cool. The solution is now supersaturated.

Now gently drop into the test tube a single crystal of thio-sulphate and watch the thermometer scale. Extremely rapid, almost instantaneous, crystallization takes place accompanied by a sudden rise of temperature. The latent heat of the solution has been given up.

This phenomenon may also be observed in the setting of plaster of Paris, by a similar experiment, for this is also a process of crystallization.

## 2. SOLDERS.

The solders used by plumbers, tinplate workers, etc. are alloys of lead and tin, made in order to secure certain useful properties not possessed by the pure metals.

**Alloys.**—If we mix two or more molten metals and allow them to set we get an *alloy*. The nature of the alloy depends upon what happens during solidification.

1. It may set into a *solid solution*, in which the constituents remain completely intermixed whatever their proportions. The resulting crystals have a composition identical to that of the liquid from which they formed, and when viewed under a microscope the structure of the alloy is indistinguishable from that of a pure metal.
2. Setting may result in separation of the constituents to form a mechanical mixture of pure metal crystals.
3. Setting may also produce a solid solution together with a mixture of pure metal crystals.
4. Finally, a mixture of solid solutions, different in composition, may be formed.

By far the greatest number of alloys belong to group 3. If an alloy consists of two pure metals that are not mutually soluble in any proportions and they are present in such proportions that one is in excess, the excess metal will separate upon setting, and the alloy will be composed

of a saturated solution of the two metals together with the excess of pure metal.

**EUTECTIC.**—If we take a pair of metals we may alloy them in any proportions, but there will be one proportion which will give the lowest setting point of the series. Such proportion is called the *eutectic ratio*, and the resulting alloy is called the *eutectic* for those particular metals, the setting point being definite.

In the lead-tin series the eutectic is composed of 37 per cent. lead and 63 per cent. tin by weight, with a setting point of 183 deg. C. (The setting point of pure lead is 327 deg. C. and pure tin 232 deg. C.)

### LEAD-TIN SOLDERS.

**EXPERIMENT 166.**—To determine the setting points of lead, tin and lead-tin eutectic.

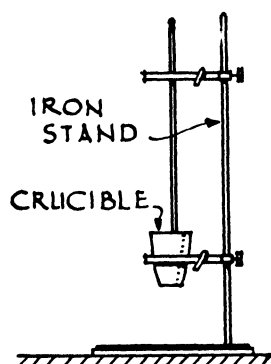


FIG. 322.—Setting Point of Metals.

Obtain a mercury thermometer reading up to 400 deg. C. and a small fireclay crucible. Place the piece or pieces of pure lead in the crucible over a Bunsen until it is melted. A Meker burner will give a quicker result than an ordinary Bunsen, but is not essential. Then place the crucible so that the thermometer may be inserted and held as in Fig. 322. Introduce the thermometer cautiously as the temperature of the lead may be well over 400 deg. When the thermometer bulb can be kept in the lead without the mercury rising to the extreme top of the scale take readings of temperature at definite time intervals as the metal is cooling. (The thermometer may be cracked if the mercury is allowed to fill the tube, and if the bulb is allowed to touch the side or base of the crucible the thermometer may burst and scatter

the molten lead. Apart from this there is no danger in the operation provided due care is taken. If desired, however, the bulb may be protected by being covered with a fireclay sheath such as is often used to cover the end of the thermocouple pyrometer.)

Cooling will proceed slowly until about 327 deg. C. is registered, when there will be a halt for several intervals (during which latent heat is being given out) after which cooling down will be resumed. The temperature indicated at the halt is the setting point of the lead.

If a sheath has not been used it may be necessary to re-melt the lead in order to withdraw the thermometer; this must be done with due caution so as not to exceed the capacity of the thermometer.

Find the setting point of tin in a similar manner, and then repeat for the eutectic. The lead and tin should be weighed out, a sharp penknife or coarse file being of considerable help in obtaining the exact quantities, 37 of lead and 63 of tin.

Plot these three cooling curves on the same graph as shown in Fig. 323.

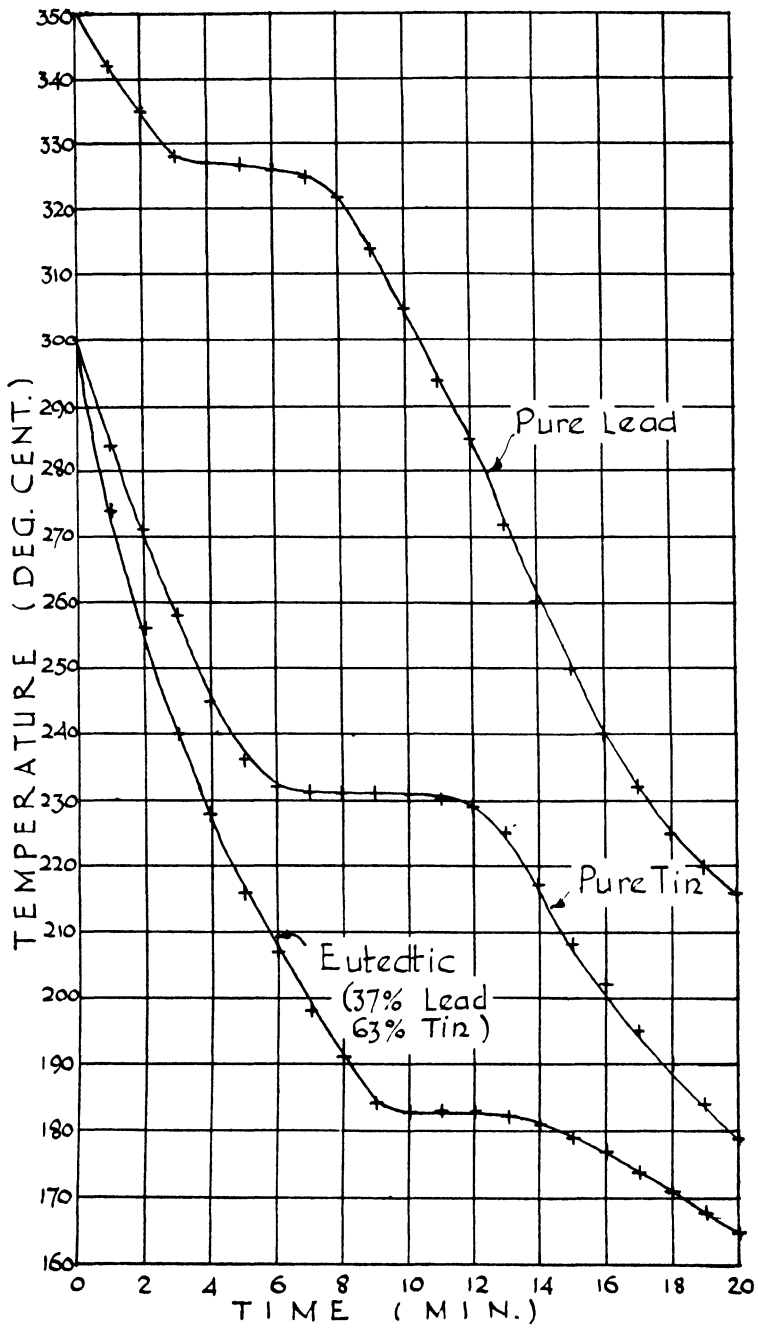


FIG. 323.—Cooling Curves for Lead, Tin and Lead-Tin Eutectic.

If there is more than 37 per cent. of lead, setting commences, at a temperature lower than 327 deg., by the separation of crystals of lead. As cooling proceeds more lead crystals separate out, leaving the remaining liquid more nearly approaching the eutectic ratio, until when this ratio is reached the remainder sets at the definite setting temperature of the eutectic, 183 deg. C.

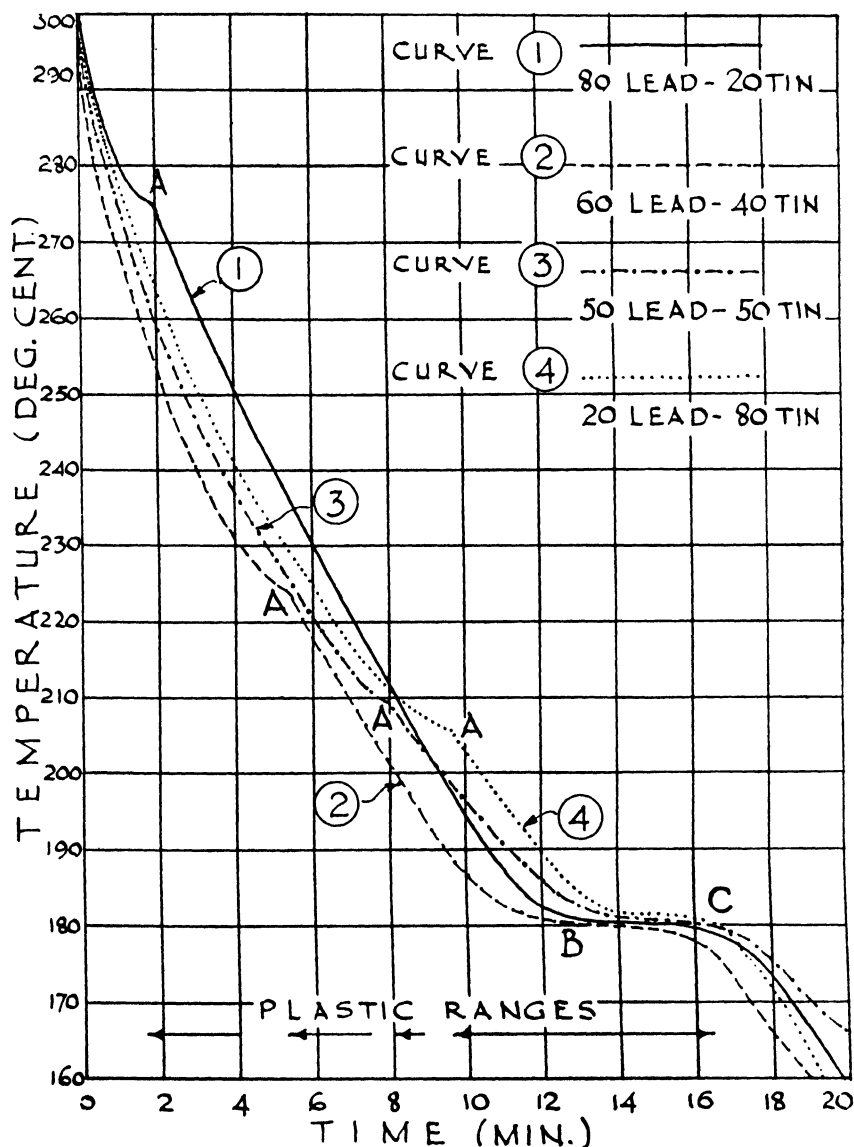


FIG. 324.—Cooling Curves for Lead-Tin Alloys.

If there is an excess of tin, pure tin separates out first until the eutectic ratio is reached, when this sets at 183 deg. C. as before.

This account of the behaviour of lead-tin alloys is only approximately correct, as the ability of liquid lead to dissolve tin varies slightly at different temperatures. Fig. 325 is therefore not strictly correct but is sufficiently so to explain the reason for the different plastic ranges of the different mixtures.

EXPERIMENT 167.—To prepare cooling curves for various lead-tin alloys.

Weigh out lead and tin in the following proportions :—

Lead ..	80 per cent.	Tin ..	20 per cent.
" ..	60 " "	" ..	40 " "
" ..	50 " "	" ..	50 " "
" ..	20 " "	" ..	80 " "

Melt each pair in turn and plot cooling curves as described in Experiment 166. These are shown in Fig. 324. The portion of the curve from A to B shows the separation of lead, and at C setting is complete, A to C representing the "plastic range" during which time the solder can be worked—as in wiping a joint, etc.

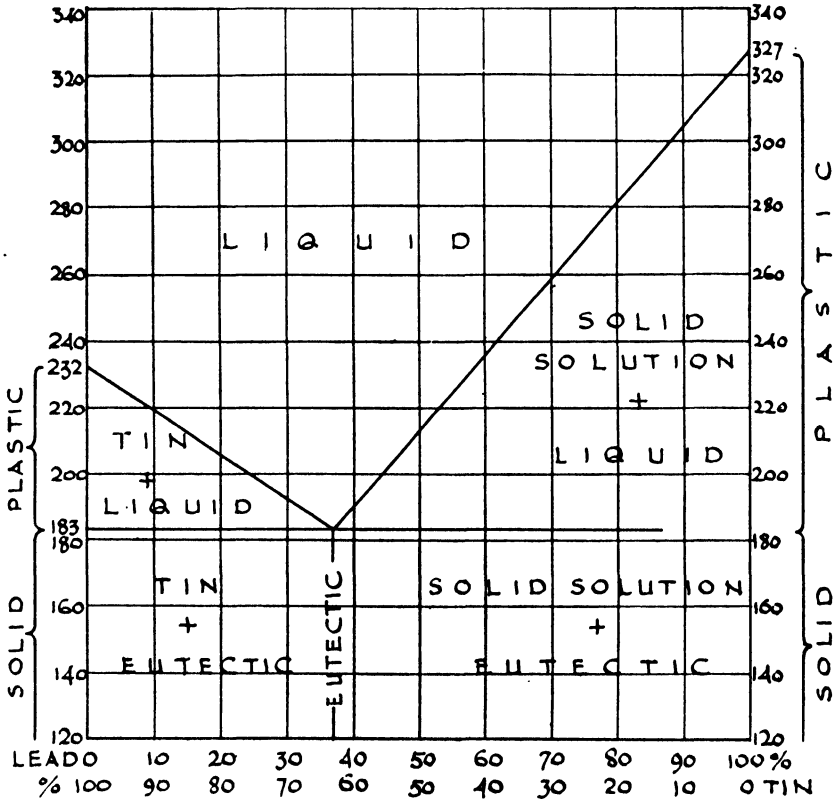


FIG. 325.—Equilibrium Diagram for Lead-Tin Alloys.

These results may to advantage be combined in a single diagram called the *equilibrium diagram* for lead and tin, and shown in Fig. 325.

Plumbers' wiping solder must have a melting and setting point well below that of lead so as to obviate the risk of its melting the pipe, etc. on to which it is poured ; at the same time it must have a long plastic stage to give plenty of time for forming the joint, and to advantage has a larger proportion of the less expensive of the two metals. It is therefore about halfway along the lead side of the diagram (Fig. 325), viz. about 70 per cent. lead and 30 per cent. tin.

Plumbers' fine solder, used for blown joints in gasfitting, etc. needs a lower melting point owing to the form of the joint, little plastic range, but for cheapness should have as much lead as possible. It is therefore about 60 per cent. lead and 40 per cent. tin.

Tinsmiths' solder needs to have a melting point well below that of tin so as not to damage tinplate, tinned copper, etc. It must also set quickly without appreciable plastic range as the joints are made with a soldering "iron." The proportions are therefore approximately 50 per cent. lead and 50 per cent. tin.

TABLE 19.  
MELTING AND BOILING POINTS. (CENT.)

<i>Substance</i>	<i>Melting Point</i>	<i>Boiling Point</i>
Hydrogen .. ..	—	—253
Oxygen .. ..	—	—182
Alcohol .. ..	—130	78
Mercury .. ..	—38.9	357
Water .. ..	0	100
Paraffin Wax .. ..	53	—
Sulphur .. ..	115	445
Tin .. ..	232	—
Lead .. ..	327	—
Copper .. ..	1080	—
Iron (Pure) .. ..	1200	—



## CHAPTER XXII

### THE ATMOSPHERE

1. *Composition of the Atmosphere.*
2. *Humidity and Condensation.*

#### 1. COMPOSITION OF THE ATMOSPHERE.

We have shown earlier that pure air is a mixture of oxygen and nitrogen in the proportions of about 1 to 4 by volume. Atmospheric air however is not pure air. When we bear in mind the constant chemical and physical changes that are occurring in all parts of the globe, together with the phenomenon of diffusion of gases, it is not surprising to find that the mixture contains other ingredients besides oxygen and nitrogen.

Its composition is approximately :—

Oxygen	..	..	..	21	per cent. by volume.
Nitrogen	..	..	..	78	„ „ „
Argon	..	..	..	·9	„ „ „
Carbon dioxide	..	..	..	·04	„ „ „
Other gases	..	..	..	·06	„ „ „

In addition there is a small variable quantity of dust, finely divided organic matter in suspension, together with water vapour.

Argon is an inert gas, like nitrogen, but unlike nitrogen it is not known to combine with other substances.

Carbon dioxide is an important constituent, and has already been discussed at length. The amount of carbon dioxide present in the outer air is insignificant, but arising as it does mainly from respiration and combustion the proportion may increase indoors to a point injurious to health. This is because its presence reduces the amount of oxygen available rather than because of any direct effects upon breathing. The proportion of carbon dioxide in the outside air is greatest in densely populated industrial districts.

The chief impurities, apart from dust and carbon compounds, are ammonia compounds derived from the decomposition of organic matter, and various industrial acids, compounds of hydrogen, sulphur, nitrogen and oxygen.

**WATER VAPOUR.**—The air always contains a certain amount of water vapour. This may be proved by a simple experiment.

EXPERIMENT 168.—To show that the air contains moisture.

Fill a small U-tube with calcium chloride and weigh it. Then connect it to an aspirator full of water and turn on the tap so that as the water flows gently from the aspirator, air is drawn through the U-tube. Again weigh the U-tube and contents. An increase in weight will be noted, due to moisture absorbed from the air.

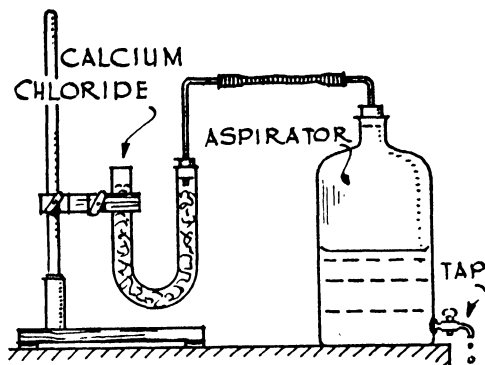


FIG. 326.—Experiment to Extract Moisture from the Atmosphere.

We have explained evaporation, and may now demonstrate it by releasing liquid into a closed space.

EXPERIMENT 169.—To show evaporation into a vacuum.

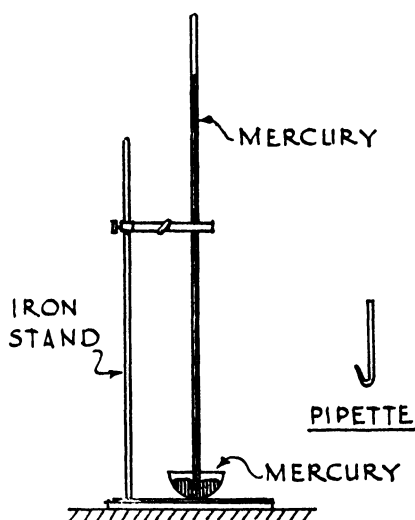


FIG. 327.—Experiment to show Liquid Evaporating into a Vacuum.

Take a glass tube 2-ft. 9-in. long with one closed end and fill it with mercury. Then, placing the finger over the open end, invert it so that the open end is immersed in mercury in a dish. Clamp the tube in this position. The mercury will fall and leave a vacuum at the top of the tube 3-in. or so high. Make a chalk mark on the tube at this level.

Now take a small bent glass tube and using it as a pipette fill it with water, introduce the end into the dish and under the open end of the mercury tube, and by easing the pressure of the finger release a drop of water. This, being less dense than the mercury, rises to the top of the mercury column and at once disappears. It has evaporated into the vacuum, and the mercury level has fallen slightly.

Release further drops of water and it will be found that after a time they take longer to disappear, and finally

remain as a layer of water on top of the mercury. It will also be found that the mercury level is now  $\frac{1}{8}$ -in. to  $\frac{1}{4}$ -in. below the mark, having been pressed downwards by the water vapour.

After the first few drops the space is partially filled with water vapour; when the water remains on top of the mercury the space is *saturated* and the vapour is exerting its maximum pressure at room temperature.

Now dip a cloth into hot water and wrap it around the top of the mercury tube for a few moments. The small amount of water lying on top of the mercury disappears, and the mercury level falls lower still. Thus the higher the temperature the more water vapour is necessary for saturation, and the greater the pressure it exerts.

Upon cooling again the small quantity of water reappears by condensation and the mercury level rises again.

From this experiment we find that water vapour exerts pressure, that the saturation point rises with increase of temperature, and that this is accompanied by increased pressure.

Repeat Experiment 169 using liquid ether instead of water. It is found that more ether than water vaporizes into the same space and that the mercury column is forced down to a very much lower level before any liquid remains unvaporized.

Again repeat the experiment with both water and ether but first introduce into the space a few bubbles of air. The mercury level falls slightly owing to the pressure of the air but otherwise the experiments proceed as before, except that vaporization is slower.

In these experiments the mercury itself is subject to evaporation, but this is so slight as to be entirely negligible.

**VAPOUR PRESSURE AND BOILING POINT.**—By a modification of Experiment 169 it can be shown that as we raise the temperature of the water vapour (or that of any other liquid) the mercury level is lowered until, when the boiling point of the liquid is reached, the mercury has sunk to the level of that in the dish. The pressure on the upper surface of the mercury inside the tube is due to the vapour, and this is then equal to the pressure on the surface of the mercury in the dish, due to the atmosphere (see page 428).

## 2. HUMIDITY AND CONDENSATION.

The water vapour in the atmosphere arises from evaporation, mainly from the oceans and other large areas of water. The rate of evaporation depends upon four things, viz. :—

- (a) The extent of the surface.
- (b) The temperature.
- (c) The dryness of the atmosphere.
- (d) The movement of the atmosphere.

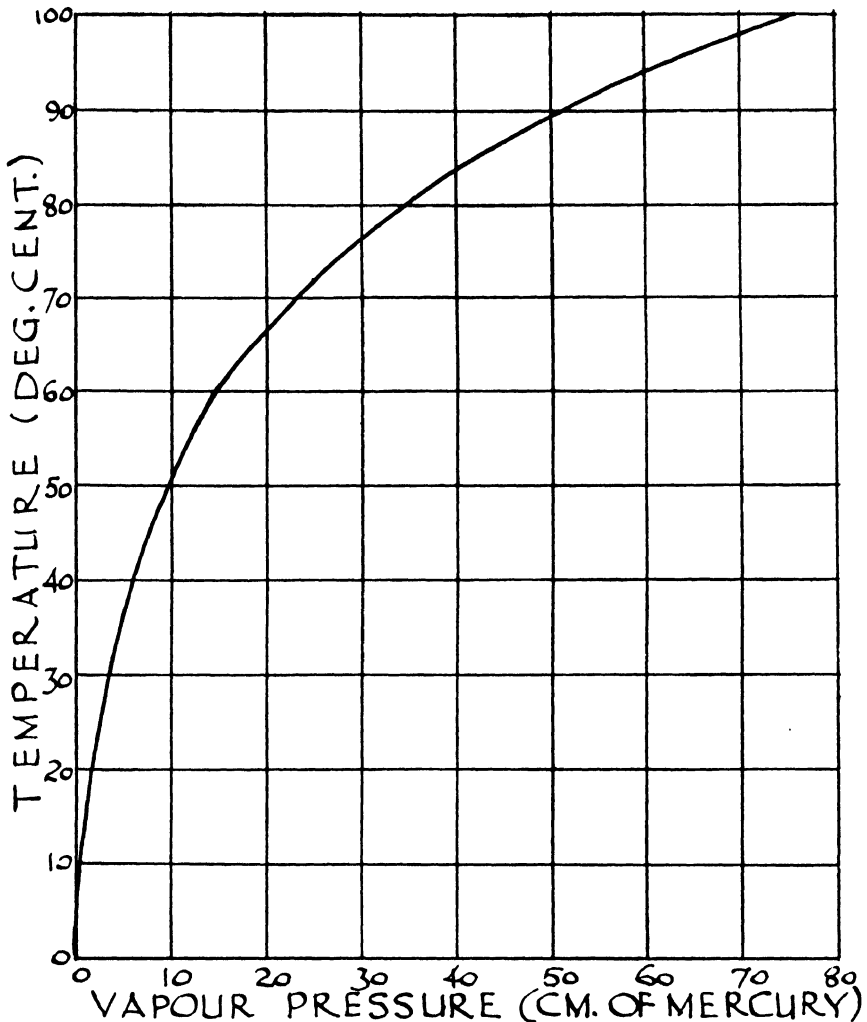


FIG. 328.—Graph showing Maximum Pressure of Water Vapour at different Temperatures.

Other things being equal, the greater the extent of the water surface the more rapid the evaporation. It is for this reason that the water area in gully and other traps is kept to the minimum.

So long as the air in contact with the water remains unsaturated evaporation continues, and as warm air does not reach saturation point so soon as cold air, evaporation is greater the higher the temperature.

The less water vapour the atmosphere contains the more rapidly does evaporation proceed, whilst when it is saturated evaporation ceases.

As air is denser than water vapour it tends to displace it upwards so that, even in the absence of wind, the water vapour rises and gives

way to drier air. Winds also promote evaporation by removing the air in contact with the water before it has reached saturation point, and bringing more unsaturated air into contact.

**RELATIVE HUMIDITY.**—The air is referred to as “damp” or “dry” according to the amount of water vapour present, but actually its state depends not only upon the quantity it holds but also upon the quantity required to produce saturation under the given conditions. The air in one room may be drier than that in another of the same size and yet contain more water vapour—if the temperature in the first room is higher. The dryness or otherwise, *i.e.* the *relative humidity*, of the air is therefore the *amount of water vapour present compared with the amount required to saturate an equal volume at the same temperature*. It is generally expressed as a percentage; for instance if a certain volume of air at a certain temperature holds 400 gm. of water vapour when saturated, but actually contains only 200 gm. its relative humidity (often called merely *humidity*) is 50 per cent.

The air in this country has a high relative humidity, varying from about 40 per cent. to nearly 100 per cent. It is seldom less than about 40 per cent. in the driest summer, whereas in desert regions it may be practically nil.

The relative humidity may be found directly by a method similar to Experiment 168, using a series of tubes and measuring the volume of air drawn through them, and although giving very accurate results it is too complicated and lengthy a process to be suitable under practical conditions. Other methods, based upon dew point or upon the loss of latent heat during evaporation, are more commonly used, and are described later.

**CONDENSATION.**—If air saturated with water vapour be cooled its saturation point is lowered and some of the vapour is condensed into liquid. This was seen to occur in Experiment 169.

In nature this liquid water is in a finely divided state and forms a *cloud* if it takes place at high level, or a *mist* if the formation is near the ground. The particles of water in mist and cloud are always tending to coalesce and fall to the earth. If the air at a low level is saturated they fall as *rain* by having collected into drops. If rain freezes by passing through a cold layer on its way to the ground the result is *hail*, whilst if freezing takes place at a higher altitude before the particles have coalesced into drops they fall as *snow*. The very large hailstones occasionally seen in a thunderstorm are usually of ice around a nucleus of snow.

During the night following a hot day, grass and other vegetation lose their heat more rapidly than the air. The air near the ground is then cooled by contact and some of its vapour condenses and settles as *dew*.

In extremely cold weather the dew is frozen and is called *rime* or *hoar frost*.

The temperature, during cooling, at which condensation begins is called the *dew point*, and at this point the water vapour has reached its greatest density and pressure.

**HYGROMETERS.**—An instrument by which relative humidity is determined is called a *hygrometer*, and certain of these work upon the principle of the gradual cooling of a glass or polished metal plate until dew is deposited. They are called *dew-point* hygrometers.

A more convenient type of instrument is the *wet and dry bulb* hygrometer which indicates the rate of evaporation by measuring the cooling effect. It is shown in Fig. 329 and comprises two mercury thermometers mounted side by side, one with its bulb exposed to the air in the ordinary way and the other with its bulb enclosed in finely woven cloth which continues downwards in the form of a wick, immersed in a container of water.

The dry bulb thermometer merely registers the air temperature but the other bulb is wet, being surrounded by the cloth which is kept wet by the capillary action of the wick, and from which evaporation is taking place. The latent heat of this evaporation is taken from the thermometer so that this thermometer

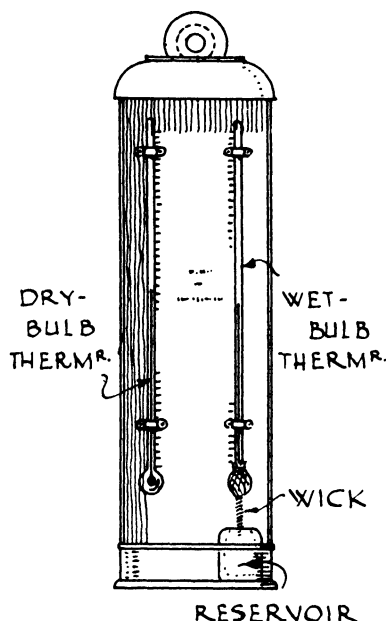


FIG. 329.—The "Wet and Dry Bulb" Hygrometer.

registers a temperature below the actual air temperature. If the air is saturated no evaporation takes place and both thermometers give identical readings. The drier the air, however, the greater will be the difference between the two readings, and by noting this and referring to a table (Table 20) the relative humidity may be found. The range of the table covers only those readings commonly met with in ordinary circumstances, and the figures for humidity percentage are found empirically by means of one or other of the dew point type of hygrometer.

**CONDENSATION ON WALLS.**—The air in a bathroom or kitchen is often warm and saturated, and the problem of condensation is thus most acute in such places. For this condensation to occur the wall surface

TABLE 20.

<i>Dry bulb thermometer reading. (Deg. F.)</i>	<i>Difference between readings. (Deg. F.)</i>																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
<i>Relative Humidity (per cent.).</i>																		
35	90	81	72	64	57	51	45	39	35	32	28	25	22	19	17	15	13	11
40	92	84	76	70	63	58	52	47	43	38	34	31	28	25	23	21	19	17
45	92	84	78	72	65	60	55	50	46	41	38	34	31	28	25	23	21	19
50	93	86	79	73	68	62	58	53	49	45	41	38	34	32	29	26	24	21
55	93	86	80	75	69	64	59	55	51	47	44	40	37	34	31	29	26	24
60	93	88	82	76	71	66	62	58	54	50	46	43	40	37	35	32	30	27
65	94	88	83	78	73	68	63	59	55	52	48	45	42	39	36	34	31	29
70	94	89	83	78	74	69	65	61	58	54	50	47	44	41	38	36	34	31
75	94	89	84	79	74	70	66	62	59	55	52	49	46	43	40	38	35	33
80	95	90	85	80	76	72	67	64	60	57	53	50	47	45	42	39	37	35
90	95	90	85	81	77	73	69	65	62	59	56	53	50	47	44	42	40	38
100	95	90	86	82	78	74	70	67	64	61	58	55	52	49	47	45	43	41

must be much colder than the air in the room unless, as in the cases just mentioned, the air is not only saturated but also at a high temperature, when only a slight difference in temperature will produce it. In other rooms such as living rooms condensation is unusual except under conditions of bad ventilation, overheating and overcrowding.

A cold wall chills the air in contact with it and results in condensation whatever its material, but a dense, smooth and impervious surface renders the condensation visible because it is unable to absorb it. Such non-absorbent materials as tiles, glass, paint, varnished papers, etc. are favoured for bathroom and kitchens and this is the chief reason for its making itself a nuisance. An absorbent surface, though often frowned upon for hygienic reasons, has the advantage of taking up the moisture and afterwards permitting it to dry out.

Apart from the question of surface texture the nature of the walling material itself is important for this decides the thermal conductivity, and therefore the rate at which heat is lost through the wall. A porous material of sufficient thickness, if dry, permits the outward flow of heat with great reluctance, and the inner face of such a wall is thus maintained at the temperature of the room. In such a case condensation would be difficult to achieve under ordinary circumstances, whereas a dense material of small thickness, whatever its surface, would appear to invite condensation. Window glass is the extreme case, being one of the densest materials, used in extremely small thicknesses, and at the same time with the most smooth and impervious surface.

**HUMIDITY AND BODILY COMFORT.**—The enervating effect of a hot, moist climate is well known. This is due not so much to the heat as to the moisture present in the air. We experience a similar effect in a badly ventilated and overcrowded room, and the reason appears to be that in such moist air the moisture exuded from our pores is unable to evaporate. It has been shown that used air, lacking in oxygen, can sustain a feeling of comparative comfort for a long time if dried and re-circulated. It is also well known that by keeping the moist, vitiated air in movement against the skin a feeling of relief from such ill-effects is experienced.

The factors affecting bodily comfort thus appear to be physiological as well as physical.

**HYGROSCOPIC MOISTURE.**—The hygroscopic moisture which is held by porous materials, and which varies in amount with the atmospheric humidity, has been discussed in Chapter IV. Deliquescence and efflorescence also have been dealt with in Chapter VIII. It remains only to emphasize the attraction of hygroscopic moisture by the types of material mentioned.



**EXPERIMENT 170.**—To show the behaviour of hygroscopic materials upon exposure.

Take two bricks of a type known to be uniform in texture and fairly porous, such as Flettons. Immerse one of the bricks in a solution of calcium hydroxide until fairly saturated, remove and dry, and then immerse it in dilute sulphuric acid. Again dry it and obtain the weight of both dry bricks. Then place both bricks in the open, but under cover, so that rain does not wet them. After a week weigh them again. Both bricks will show an increase in weight which should be calculated as a percentage increase over the dry weight. The treated brick will be found to have absorbed a much higher percentage of moisture than the untreated brick.

Dry both bricks again, and the treated brick will show considerable efflorescence—calcium sulphate.

## HEAT TRANSMISSION

1. *Convection.*
2. *Conduction.*
3. *Radiation.*
4. *Heat Insulation.*

When heat is propagated at a particular point it always tends to disperse. It can become dispersed in three distinct ways, each of which will be explained before considering its practical significance.

### 1. CONVECTION.

When a particle of matter becomes heated the range of vibration of its molecules becomes greater and it expands. But a given molecule still has the same mass as before, consequently the density of the matter is reduced. In a solid this fact has little significance, but in a fluid, where the particles are free to move throughout the substance, it gives rise to a *convection current* in the body of fluid.

These currents are brought about by reason of the fact that the unheated particles of a fluid are more dense than the newly heated ones and thus gravitate towards the lowest point of the body of fluid. In doing so they displace upwards the hot particles. It should be remembered that the hot particles, whether of liquid or gas, have no ability in themselves to rise; they rise only because they are pushed from beneath, and the difference in weight between hot and cool particles is the only force acting. It follows from this that the greater the difference in temperature between the hottest and the coolest particles the more vigorous will be the current produced.

If the source of heat be maintained, the cooler particles, already in motion as a result of their greater weight, become heated in turn, whilst the previously heated particles having been displaced away from the heat source lose some of their heat to the surroundings and become in turn the cooler particles. The convection current is thus continuous and is then described as a *circulation* within the body of fluid.

**EXPERIMENT 171.**—To show convection currents in a body of liquid.

Support a large round flask as in Fig. 330, fill it with water, and drop into it one or two crystals of potassium permanganate or magenta dye. Then apply heat from a very small flame as shown. When the flame is applied centrally as at A the current will be seen

to follow the direction of the arrows, rising up the middle and descending around the sides. Upon moving the source of heat to one side the circulation will be seen to change in the manner shown at B.

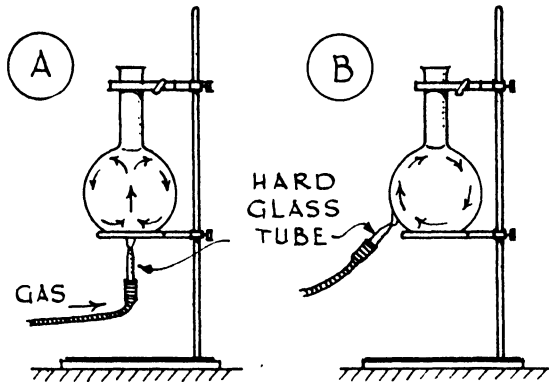


FIG. 330.—Convection Currents in Water.

Fig. 331 shows how a body of liquid may be contained in two distinct vessels connected by pipes. Heat is applied to the liquid in the lower vessel (the "boiler") whereupon, owing to the difference in the levels of the two pipes, the convection current flows up the *flow* pipe to or near the top of the higher vessel (the "storage vessel"), returning from the bottom of this via the *return* pipe to the bottom of the lower vessel. Here it is re-heated, and so the circulation proceeds until the water in the upper vessel has attained almost the temperature of that in the lower one.

**HOT WATER SYSTEMS.**—This is the principle underlying all hot water heating and supply systems. In such systems the *rate* of circulation is governed solely by the difference in temperature of the hottest water (that leaving the

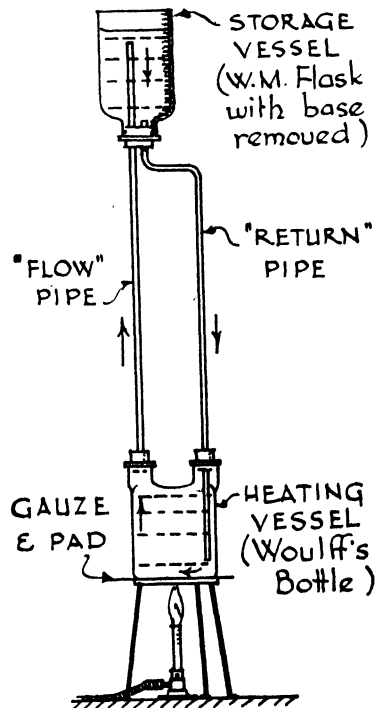


FIG. 331.—Experimental Hot Water Circulation.

boiler by the flow pipe) and the coolest (that re-entering the boiler by the return pipe). The *force* causing the circulation is solely the difference in weight between the cool "column" of water and the hot "column."

Assuming the hot column (the flow pipe, etc.) to have an average temperature of 50 deg. C., and the cool column (the return pipe, etc.) 20 deg. C., and that the pipes are 10 sq. cm. in cross section and 10 m. high, we can easily calculate the force of the circulation.

At 20 deg. C. the density of water is .9982 gm. per c.cm., whilst at 50 deg. C. it is .9881 gm. per c.cm.

The volume of water in each vertical column is  $1,000 \times 10 = 10,000$  c.cm., and the weight of each is :—

Weight of cool column =  $10,000 \times .9982 = 9982$  gm.

„ „ hot „ =  $10,000 \times .9881 = 9881$  gm.

The difference in weight is therefore  $9,982 - 9,881 = 101$  gm.

The data assumed approximates to practical conditions and it will thus be clear that the force behind such a circulation is very small indeed, so small in fact that a large air bubble may cause serious interference if trapped in a bend or "horizontal" portion of the circulating pipes. It is for this reason that any "horizontal" portion should have an appreciable rise in a direction away from the boiler; air is thus better able to escape to the highest point in the system, the top of the "expansion" pipe.

Fig. 332 shows diagrammatically the simplest types of low-pressure supply and heating systems—the "cylinder" supply system and the one-pipe "drop" heating system.

Where a speedier circulation is required it may be forced, by inserting a power-driven pump or impeller in the circulation. This is more usual in cooling systems where the object is to dissipate heat by circulating cool liquid around the parts concerned.

**CONVECTION IN GASES.**—Our examples of convection currents have so far been confined to liquids. Gases, however, are also fluids and are included in our general explanation of the nature of convection currents.

**EXPERIMENT 172.**—To show convection currents in a body of air.

The apparatus shown in Fig. 333 comprises a wooden box with a removable air-tight glass front and two holes in the top through which glass chimneys are fitted. Chimney A is provided with a closely fitting metal cap.

Place a burning candle under Chimney B, close the glass front and fit the chimney cap at A. After a time the candle flame shows signs of approaching extinction as the oxygen in the box is used up. Upon removing cap A the candle immediately burns brightly again, showing that air is entering via chimney A to displace the products of combustion via chimney B. If a piece of smouldering material be held at A smoke will be seen to travel down A, across the box and up B, so demonstrating the continuous convection current produced by the heat from the candle flame.

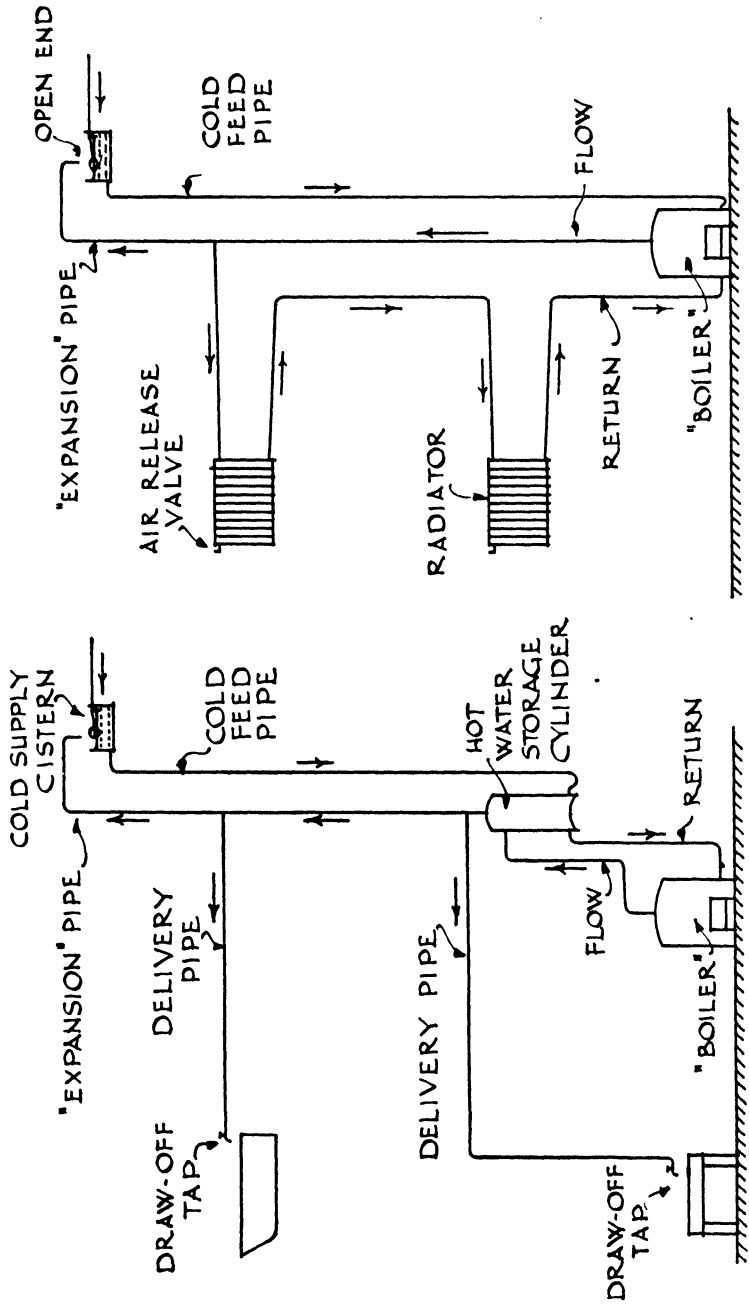


FIG. 332.—Simple Types of Hot Water Supply and Heating Systems.

Systems of "natural" ventilation of buildings depend for their working upon these convection currents. A fireplace in a room ensures a current of air whenever the air in the room is warmer than that outside, although the fireplace opening is too low to ensure thorough changing of the air in the upper part of the room.

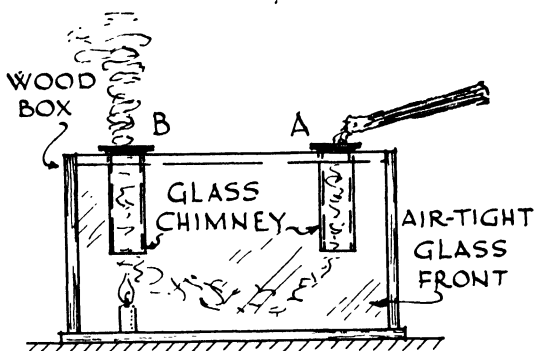


FIG. 333.—Convection Currents in Air.

In certain old-fashioned ventilating systems the outlet flue was often provided with gas jets at its base in order to speed up the extraction of the used air, on the principle of Experiment 172.

## 2. CONDUCTION.

In the case of a solid the increased vibration due to a rise in temperature of one part is imparted by "contact" to adjoining molecules, *et seq.* Thus if a metal rod were heated at one end it would ultimately attain uniform temperature throughout its length, but for the fact that some of the heat is lost to the air from its exposed surface. This method of transmission is called *conduction*, and (except in negligible degree with fluids) is confined to solids because of their rigid structure.

Solids are classed as good and bad conductors according to their readiness or otherwise to conduct heat. Metals are good conductors, timbers are bad conductors—hence the wooden handle on a soldering bit, etc. In cold weather, out of doors, the metal parts of a shovel "feel colder" than the wooden parts, yet we know that both are of the same temperature. If, however, the same shovel is in a hot situation such as by a furnace door the metal parts "feel hotter" than the wood, yet again both are at the same temperature.

**EXPERIMENT 173.**—To show the high conductivity of metals.

Obtain two countersunk wood screws, size 2-in.  $\times$  No. 12, one of steel and the other of brass, or, if possible, copper.

Take a piece of  $1\frac{1}{4}$ -in. wood and insert the screws so that the heads are exactly flush, then cut off and file down the other ends of the screws. To make sure that the screw heads are level the whole surface should be rubbed on sandpaper or emery cloth. Stick down a square of gummed paper over the screw heads, and dip the other side of the wood lightly in molten wax so as to form a thin film when set.

Now hold the wood horizontally in a small Bunsen flame, paper side down. Watch the waxed upper surface carefully and very

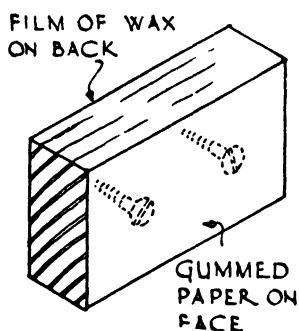


FIG. 334.—To Compare the Conductivity of Metals and Wood.

soon the wax will melt in a small circular "blob" over the end of the copper or brass screw, followed soon afterwards by melting over the steel or iron screw. The screws have thus conducted the heat through their length at different rates whilst insufficient heat has travelled through the wood to have any visible effect upon the wax.

Now turn the wood over and examine the other side. The paper will be charred where it was in contact with wood but not where it touched the screw heads. Although the whole was heated more or less uniformly, the metal screws conducted the heat away so rapidly as to prevent charring, whilst the wood resisted this rapid conduction and so permitted the paper to be charred.

This experiment shows in a general way that materials differ in their heat conducting power or *thermal conductivity*. The next experiment goes a little further and enables certain materials to be placed in order in this respect.

EXPERIMENT 174.—To compare materials for conductivity.

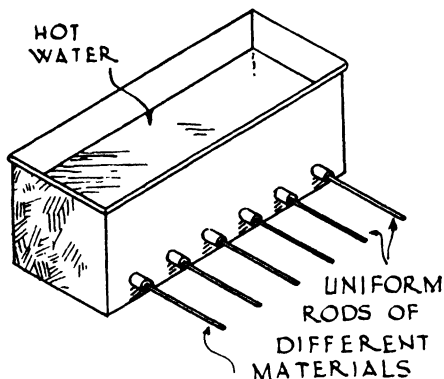


FIG. 335.—To Compare the Conductivity of Materials.

The apparatus comprises a metal tank with a row of holes along one side into which are fitted one-hole rubber bungs. The specimens are in the form of thin rods of metals, glass, etc., and are inserted in the bungs after having been coated with paraffin wax.

Water at a temperature approaching boiling point is then poured into the tank so as to submerge the inner ends of the rods. The wax will be observed to melt from the rods for different distances according to their degree of conductivity.

From the Building viewpoint the severe limitations of this method are evident, because the object of our investigations may be a brick wall or a concrete roof slab. In principle, however, the methods used are similar and are dealt with later.

The high conductivity of metals may be shown in a number of ways with wire or wire gauze. The well-known car radiator lamp (or the miners' safety lamp) is merely a paraffin wick lamp in which the flame burns in a space enclosed by copper or brass gauze. The inflammable gases, along with air, reach the flame and may burn inside the gauze, but do not burn outside it because the heat of the flame is dissipated so

rapidly over a large area of the gauze as to reduce the outside temperature to a point below the ignition point of the gas.

**EXPERIMENT 175.**—To show the rapid conduction of heat through copper gauze.

Hold a square of copper gauze horizontally over a medium Bunsen flame and gradually lower it. The flame is gradually "cut off" as at A in Fig. 336, until when the gauze rests on the Bunsen itself it may be extinguished altogether. Yet the gas has passed through the gauze as may be shown by reversing the experiment, starting with the gauze just above the burner, igniting the gas *above* it, and then raising the gauze as at B.

Fold a piece of copper gauze so as to form a flat cone and lay it on a glass beaker as in Fig. 337. Now take a metal ladle containing methylated spirit, ignite it and carefully pour the burning spirit on to the gauze. It passes into the beaker but is extinguished in passing through the gauze, not by any lack of oxygen but because its temperature has suddenly been reduced below its point of ignition.

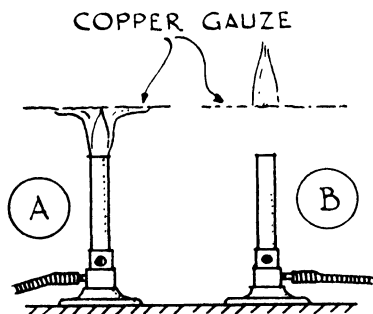


FIG. 336.—Rapid Dissipation of Heat by Metal Gauze.

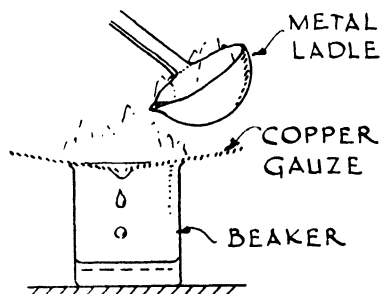


FIG. 337.—The High Conductivity of Copper Gauze.

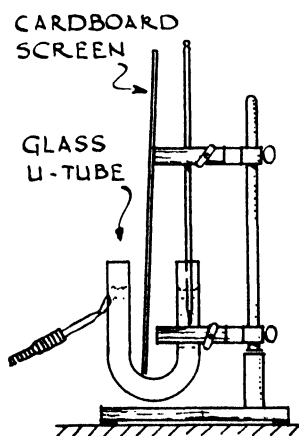


FIG. 338.—Showing the Poor Conductivity of Water.

**CONDUCTION IN LIQUIDS AND GASES.**—In any normal body of liquid or gas the particles are displaced by convection before any appreciable transfer of heat by conduction can take place. Even when convection can be prevented, such as when water or air is held in the pores of a solid, they are very bad conductors, gases being worse than liquids.

**EXPERIMENT 176.**—To show that water is a bad conductor of heat.

Fit up a glass U-tube of water with a thermometer bulb immersed in one arm (Fig. 338). With a small flame heat the water near the top of the other arm until it boils. The thermometer will register little or no change, especially if screened by a piece of cardboard, because the heat cannot travel *downwards* through the water to the other arm of the tube by convection, but only by conduction.



### 3. RADIATION.

In convection heat is transferred from one point to another *by the relative movement of particles* (quite distinct from the heat motion of the molecules). In conduction transference is *between adjoining particles which do not move relative to each other*. In radiation the molecular heat motion of a body causes to be sent out or radiated into space rays or waves, travelling in straight lines, in all directions from the source, and at a speed of about 186,400 miles per second.

All hot bodies give out these waves, the bigger and hotter the body the more intense the waves. They must not however be thought of as waves of *heat* but as waves of energy which when directed on to a body *produce* sensible heat in the body. The heating effect of the sun upon the earth is due to radiation but the heat does not travel between the two any more than the voice of the telephone operator travels along the wire to the receiving end.

Heat radiation travels best through empty space but can also travel through various media. The atmosphere has little effect upon it, and is too attenuated to be warmed by it, so that it is received, uninterrupted, by the earth's surface, from which the air is heated mainly by convection.

Heat radiation is subject to many of the laws which govern light radiation; in fact it is scarcely correct to refer to them as different *kinds* of radiation—rather ought they to be considered as different *degrees* of radiation.

If a filament is placed in a darkened room and a gradually increasing electric current passed through it its molecular vibrations slowly increase and it emits radiation. At first the vibrations have a *low frequency* or *long wave-length*, but as it gets hotter so is the frequency of the radiation raised (or the wave-length shortened). As yet the filament is invisible to the eye and is emitting mainly heat radiation, but soon it begins to show up dull red. The radiation still produces the sensation of *heat* on the skin but now also produces the sensation of *light* on the eye. As the frequency increases (or the wave-length decreases) so the filament passes through the spectral colours in order—from red to orange, then to yellow, green, blue, indigo, and violet. We do not distinguish the separate colours with the naked eye for after bright yellow the light appears to us as white. Radiation still continues after the violet stage but no longer produces the sensation of light—these are the “ultra-violet” rays, whilst those emitted before the sensation of light commenced were the “infra-red” rays. Infra-red rays are very “heat producing” but not very actinic, whilst the ultra-violet are very actinic, but their heating power is negligible.

It can be shown that the intensity of heat produced by radiation depends upon the distance from the source, being *inversely proportional to*

*the square of the distance.* Thus, if the distance from the source is doubled the same amount of radiation affects four times the area and the intensity is thus one quarter; if the distance is trebled the area is nine times and the intensity one-ninth, etc., etc., as illustrated in Fig. 339.

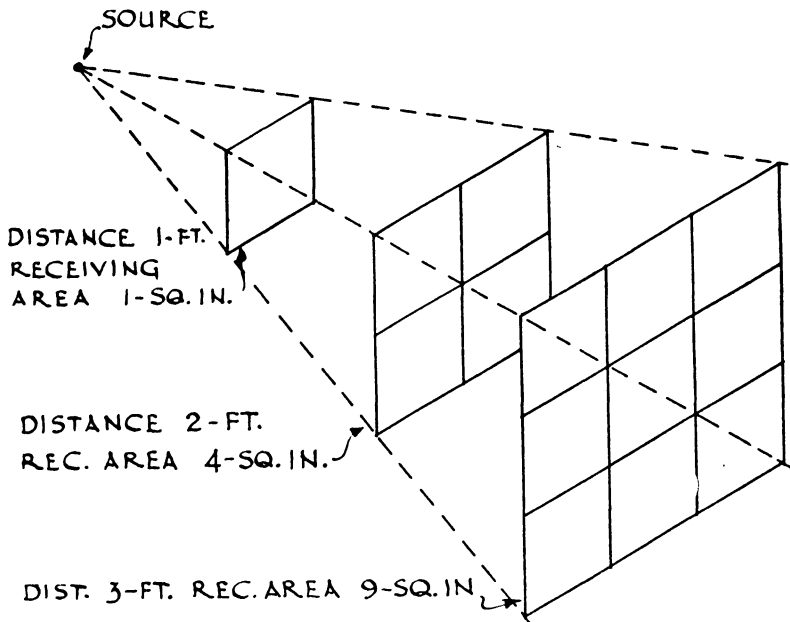


FIG. 339.—Illustrating the Law of Inverse Squares.

**EMISSION OR RADIATING POWER.**—As radiation takes place from the surface of a body the type or state of the surface, affects the extent to which emission by radiation will occur, quite apart from the temperature of the body. For any given temperature, and through any given medium, the emission will therefore depend solely upon the type of surface—whether rough or smooth, dark or light in colour, etc.

**EXPERIMENT 177.**—To compare the heat emission of different surfaces.

A convenient way of ensuring uniform temperature, etc. is to use a "square" metal container which may be filled with hot water, and the sides of which may be treated to give the required variation of surface. Such an arrangement is shown in Fig. 340, the container having its four sides treated as follows:—

- (a) Painted dead black (matt or dull).
- (b) Painted dead white.
- (c) Painted aluminium paint.
- (d) Untreated except for high polish of tinned surface.

The container is suitably supported, filled with hot water, a thermopile placed in position and the scale reading of the galvanometer taken.

The container is now turned so that another face is opposite to the thermopile, and the same distance from it, and a new reading taken. This is repeated until all four are recorded, but should be done quickly as the temperature of the water is falling slightly throughout the experiment.

In this experiment the dead black surface will be found to give by far the highest reading and if this is taken as unity the others may be related to it, so expressing the results as *coefficients of emission*. The results will be approximately :—

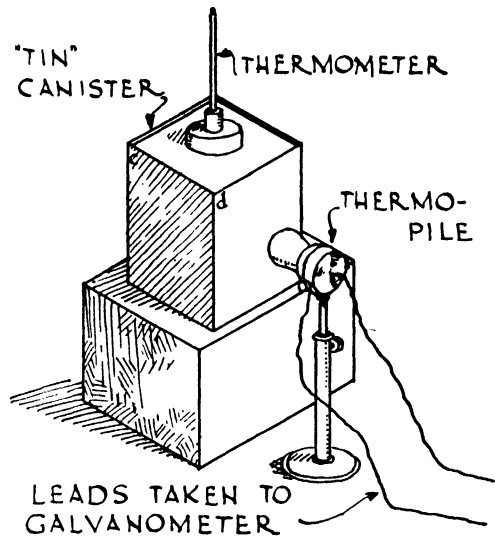


FIG. 340.—Comparing Surfaces for Heat Emission.

Surface					Coefficient
Dead black .. .. .	..	..	..	..	1.0
Dead white .. .. .	..	..	..	..	.2
Aluminium .. .. .	..	..	..	..	.05
Polished tin .. .. .	..	..	..	..	.02

Further containers may with advantage be prepared, using various colours each with a matt and a glossy surface. It will be found that in general the coefficient is lower for the lighter colours and that the effect of the glossy finish is to reduce it still further.

In connection with heat emission the practical case to come first to mind is the hot water "radiator" or heating pipes. From Experiment 177 it was found that, other things equal, a dull black surface allowed most heat to be emitted by radiation—about twenty times as much for instance as an aluminium painted surface. This result is equally true of pipes and radiators in a heating system as of the water container in the experiment; if they were all to be finished in a dull black paint they would be most efficient, but in practice the advantage to be gained would be very slight and scarcely worth while. For instance if a thermopile were used to measure the radiation from a dull black radiator and from an aluminium painted one the proportion of about 20 to 1 would be noted. But if two identical rooms were heated in an identical way, but one having

dull black and the other aluminium painted pipes or radiators, the temperatures maintained in the rooms would not be in the proportion of 20 to 1—they would be almost equal. This is because in such a method of heating radiation is the least important means of transmitting the heat. Of the heat given out to the room from pipes and radiators only about one quarter is by radiation, the rest being by convection with the air as the medium.

Electric “fires” and open fires heat a room mainly by radiation, the heat being emitted from the glowing wires or fuel, but gas fires heat mainly by convection unless so designed as to expose an appreciable incandescent area. Imitation coal fires, whether electric or gas, are inefficient in all practical respects and cannot be considered seriously.

**ABSORPTION OF HEAT RADIATION.**—When heat radiation impinges on a surface it is partly absorbed (and so converted into heat) and partly reflected, or even transmitted through it, according to the type of surface. The ability of a surface to emit and to absorb heat radiation is identical—thus a good emitter as also a good absorber, and consequently a bad reflector.

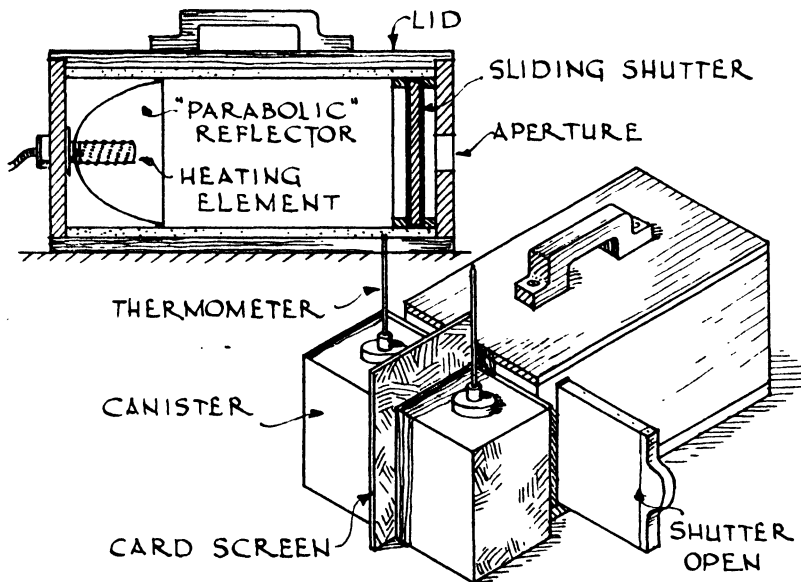


FIG. 341.—Comparing Surfaces for Heat Absorption.

**EXPERIMENT 178.**—To compare heat absorption of different surfaces.

Fig. 341 shows an easily constructed box, lined with slab cork or several thicknesses of softboard, with an electric heater at one end and an aperture in the opposite end against which may be placed

specimens of different materials. Covering the aperture is a sliding shutter arranged so as to expose the specimen to the radiant heat when withdrawn. The shutter or screen may conveniently be made of a square of insulite or other softboard covered on both faces with sheets of polished tinplate. Mere switching on of the heater element, without the use of the shutter, is not conducive to good results because it takes some time to attain its maximum temperature on each occasion. If the aperture is made 2-in. high and  $7\frac{1}{8}$ -in. wide its area is almost exactly  $\frac{1}{10}$  of a square foot and is a convenient size for most specimens and for most purposes.

For the present experiment stand two containers (as used in the previous experiment) side by side against the aperture so that equal areas will be exposed to the radiation from the heater. Fill both with cold water and arrange them so that one dull black surface and one bright tinned surface are exposed. See that both thermometers read alike, then switch on the heater and when it is fully operating withdraw the shutter and then compare the two temperatures from time to time. The container exposing its black surface will heat up more rapidly than the other, showing that this surface absorbs heat radiation faster than does the bright surface.

For low temperature such as those we have considered in these experiments the coefficients of emission and absorption are identical, and for different surfaces are as found and recorded. When dealing with radiation from intensely hot bodies, however, such as the sun, the behaviour of the various surfaces is rather different. As before, dull black absorbs most, but then follow in order aluminium paint and polished metal, the white surface being last and therefore the worst absorber.

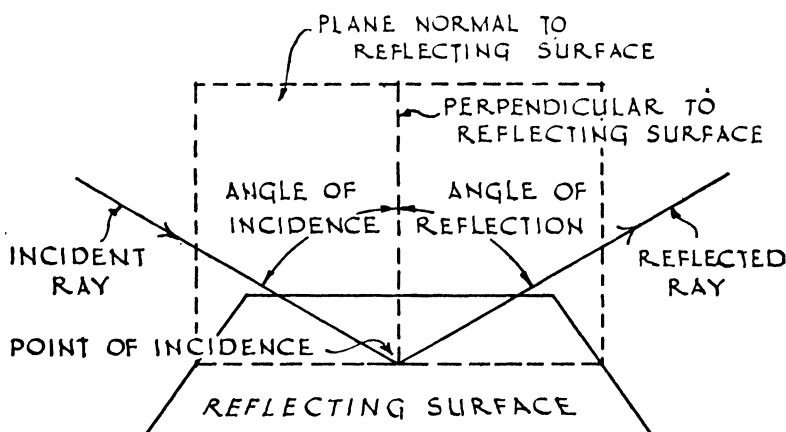


FIG. 342.—Reflection of Heat from Plane Surface.

**REFLECTION OF HEAT RADIATION.**—Fig. 342 shows a reflecting surface with an incident ray meeting it. From the point of incidence imagine a perpendicular or normal to the reflecting surface. Then the ray is reflected

in a straight line from the point of incidence so that the *angle of reflection* is equal to the *angle of incidence*, and so that it lies in the same plane as the incident ray and the normal.

Fig. 343 shows that this is true whether the reflecting surface be plane or not.

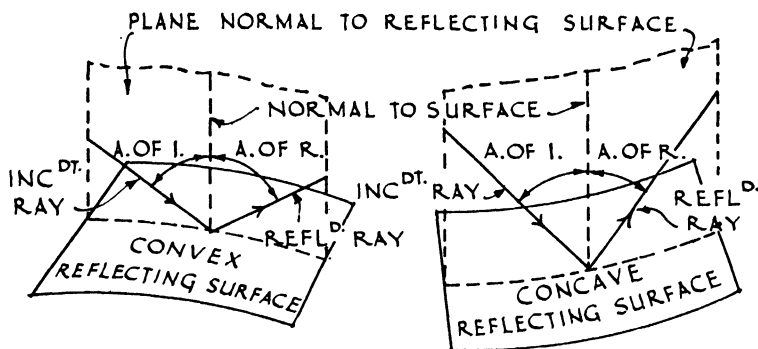


FIG. 343.—Reflection of Heat from Curved Surfaces.

**EXPERIMENT 179.**—To show the reflection of heat radiation.

The heater box described in Experiment 178 is used, the aperture being modified by placing over it a piece of softboard in which a 1-in. diameter hole has been formed. Two cardboard tubes, each 2-ft. long and 2-in. in diameter are required, supported horizontally in a suitable way such as shown in Fig. 344, together with a thermopile and two sheets of tinplate, one polished and the other painted dull black.

Arrange the box, tubes and thermopile as shown, but do not place the reflector in position. Switch on, and note the behaviour of the galvanometer—it will be unlikely to be affected. Now bring the polished reflector into position, adjusting it bearing in mind that the angles of incidence and reflection should be equal. When the correct position has been found the galvanometer will show an appreciable reading. Remove the polished reflector and substitute the blacked one—a slight reading may be recorded, but nothing approaching the previous one.

Various other types of surface should be tried and placed in order of reflectivity. In addition the angle between the tubes should be varied to find the positions giving the best results; this will be found to be about 120 deg.

With regard to the reflecting power of polished metallic surfaces it is worth recording that, although not affecting the appearance of the surface, a coat of colourless transparent varnish materially reduces the reflectivity. For instance it has been found that a coating of lacquer .001-in. thick reduces the efficiency to 20 per cent.

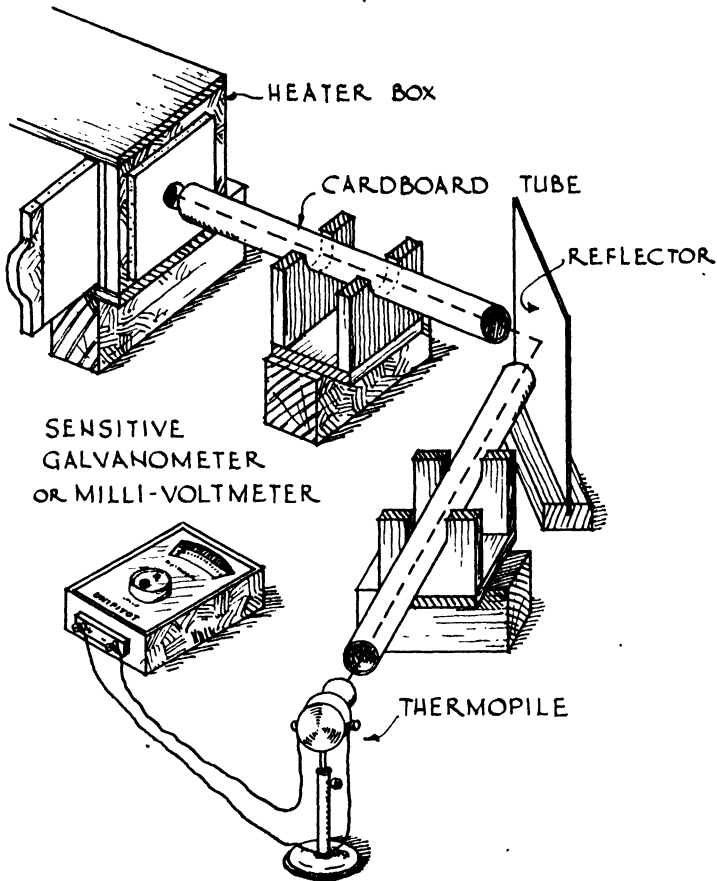


FIG. 344.—Experiment on Heat Reflection.

**TRANSMISSION OF HEAT RADIATION.**—Some substances permit heat radiation to pass through them without becoming perceptibly heated by it. This property is called *diathermancy*, and the substance is said to be *diathermanous* (corresponding to *transparency* to light). The atmosphere is diathermanous, but water vapour is not—atmospheric moisture therefore partially obstructs heat radiation and in moist climates prevents undue heat loss by radiation during the night.

Water itself does not transmit heat radiation and may thus be used to pass light whilst at the same time barring the passage of heat.

Glass acts in a selective manner. It is transparent to light and also to a great extent it is diathermanous with respect to bodies at extremely high temperatures, such as the sun, but at lower temperatures it absorbs the rays and becomes heated instead of transmitting them. Window glass thus admits solar radiation which warms objects within the room

and so assists in keeping the room warm, whilst not permitting the radiation from the room, that from fires included, to escape outwards. This is, of course, irrespective of its behaviour with regard to convection and conduction.

**REFRACTION OF HEAT RADIATION.**—Heat rays passing from one medium to another are refracted or “bent” exactly like light rays. They are therefore capable of being focussed by a lens, the intensity of heat produced when they are so concentrated being sufficient, in the case of solar rays, to ignite combustible materials.

#### 4. HEAT INSULATION.

By this we mean the property of a material or construction of resisting the passage of heat from one face to the other, so “blanketing” or isolating thermally the space or construction which it encloses. The term is also used to signify the insulating material itself.

The lagging with which steam boilers and pipes are surrounded is an excellent example. Its function is to reduce to a minimum the loss of heat from the metal surface of the pipe, etc., to the surrounding air by convection, and to a smaller extent through the air by radiation. These requirements are best met by the use of an adequate thickness of material having low conductivity, its surface being whitened to reduce loss by radiation of the small amount of heat which may reach its surface by conduction.

In the case of cold storage construction the requirement is not to keep heat in but to keep it out. This is, however, an identical problem, and is met by some form of hollow construction filled with badly conducting material, with sometimes in addition a heat-reflecting surface of metal foil. Typical construction is shown in Fig. 345.

The perfect example of insulation is the Dewar or Thermos flask. Its everyday use is to “keep hot” the liquid placed in it, but the use for which it was invented was the reverse of this. It consists really of two glass vessels connected only across the mouth, the air being withdrawn from the space between them, and the inner surfaces silvered (and thus showing silvered on the outer surfaces too). Let us see in what way heat can escape from hot liquid in the flask to the outer air. The liquid is in contact with the outer face of the inner glass wall and heat passes by conduction through its thickness to its inner face. It cannot go further by conduction except at the extreme rim (and the liquid is not in contact with the glass at this point) or across the cork (and cork is one of the worst of solid conductors). It cannot travel at all by convection since the space between the walls contains no medium in which currents can be set up. It can therefore travel across the vacuum only by radiation. Experiments 177 and 178 showed us that a silvered surface is the least



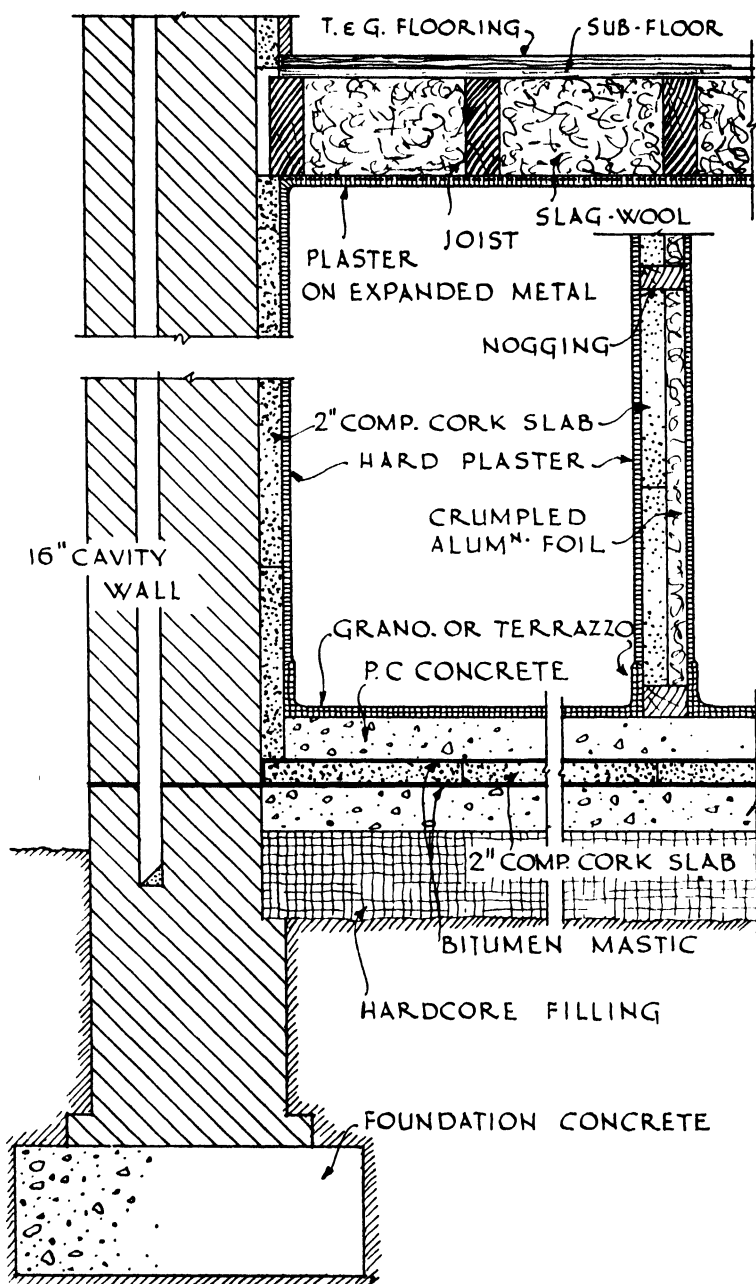


FIG. 345.—Typical Cold Storage Construction.

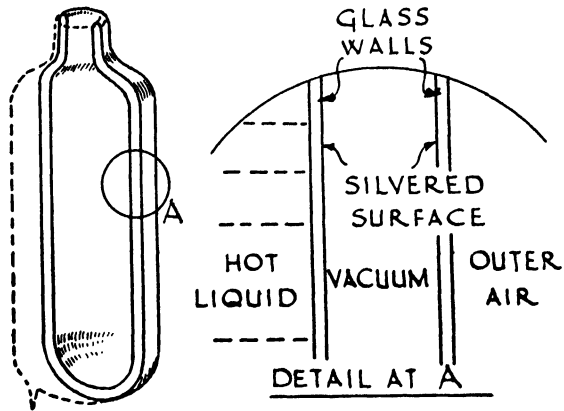


FIG. 346.—The "Thermos" Flask.

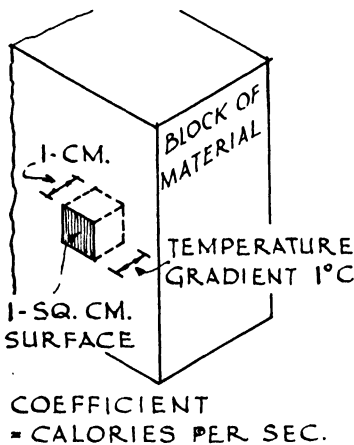


FIG. 347.—Metric Coefficient of Thermal Conductivity.

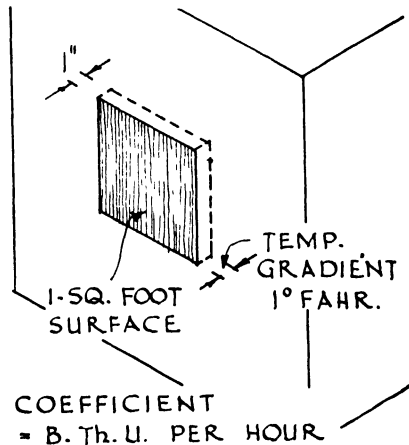


FIG. 348.—British Coefficient of Thermal Conductivity.

efficient heat emitting and heat absorbing surface, and here the heat, if it is to pass, must be emitted by one silvered surface and absorbed by another before reaching the outer glass wall. The infinitesimal amount of heat getting thus far through the defence has still to be radiated from a silvered surface (the outer face of the outer wall) or passed to the metal outer case by convection currents in a very limited body of air, or by conduction through a cork pad at the base (the usual means of ensuring rigidity). The high efficiency of these flasks is therefore not surprising, but this high efficiency is clearly impossible in building construction, nor is it necessary.

**Transmission of Heat through Walls.**—The loss of heat through the walls of a building (taking the usual case of heat loss outwards from the interior) is due to :—

- (a) Flow of heat from the warm air inside to the inner face of the wall. (Convection.)
- (b) Flow of heat through the wall from the inner to the outer face. (Conduction in the case of solid construction, plus convection and to a small extent radiation in the case of a cavity wall.)
- (c) Flow of heat from the outer face of the wall to the cold air outside. (Convection.)

So far as (a) is concerned, experiments carried out at the Building Research Station have shown that by the use of a metal-faced wallpaper on the internal surfaces of the external walls the air of a room is maintained at a materially higher temperature for the same fuel expenditure. This is because they partly reflect heat radiated from the internal walls, furniture, etc., consequently absorbing less.

Heat loss under (c) is naturally most difficult to assess since it is affected by the movement of the external air as well as by the difference in temperature between it and the wall surface. Nevertheless, other things equal, the rate of heat loss through the wall will depend upon the conductivity of the wall itself.

**THERMAL CONDUCTIVITY.**—The readiness with which a substance conducts heat through its thickness may be measured and expressed as a *coefficient of thermal conductivity*. Consider a large block of the material with at least one plane surface, and a 1-centimetre cube in the body of the block with one face forming part of the plane surface. Heat applied uniformly and constantly to the plane surface will pass by conduction through the block to the other faces, from which it will be lost to the surroundings. But considering the small cube the heat will pass through it at right-angles to the face, and the temperature over the rear face will be less than over the front face. This temperature difference is called the *temperature gradient*, and is reckoned as 1 deg. Centigrade for the purpose of defining the coefficient.

The coefficient is *amount of heat passing through 1 sq. cm. in 1 second divided by temperature gradient per cm. (1 degree)*. In Metric units it may thus be defined :—*The coefficient of thermal conductivity for a material is the number of calories passing per second through a 1 cm. cube of the material for a temperature gradient of 1 deg. Cent.*

In British units (used by heating engineers in this country) it is *the number of B.Th.U. passing per hour through 1 sq. ft. of the material 1-in. thick for a temperature gradient of 1 deg. Fahr.* This is clearly a very much

larger unit, in fact a Metric value of 1 is equivalent to a British value of 2,903, but as will be seen from Table 21 most Metric values are very much less than unity, so that for practical purposes the British unit is more manageable.

TABLE 21.  
COEFFICIENTS OF THERMAL CONDUCTIVITY FOR MATERIALS.

<i>Material</i>	<i>Coefficient</i>	
	<i>Metric</i>	<i>British</i>
Silver .. .. .	1·006	2,920
Copper .. .. .	·92	2,671
Aluminium .. .. .	·5	1,452
Zinc .. .. .	·26	755
Brass .. .. .	·26	755
Tin .. .. .	·16	464
Mild Steel .. .. .	·13	377
Lead .. .. .	·08	232
Marble .. .. .	·007	20·3
Gravel concrete (av.) .. .. .	·0024	6·9
Limestone (av.) .. .. .	·0024	6·9
Sandstone (av.) .. .. .	·0022	6·5
Fletton brick .. .. .	·0022	6·5
Glass .. .. .	·0017	4·94
Water .. .. .	·0014	4·06
Pumice concrete (av.) .. .. .	·00044	1·3
Softwood (across grain) .. .. .	·00034	1·0
Paper .. .. .	·0003	·87
Slag wool .. .. .	·00016	·46
Softboard .. .. .	·00014	·4
Wood chippings .. .. .	·00013	·38
Sawdust .. .. .	·00012	·35
Cork slab .. .. .	·00011	·31
Felt .. .. .	·00009	·26
Granulated cork .. .. .	·000087	·25
Air .. .. .	·00006	·17

The actual measurement of the conductivity of building materials involves advanced methods and the use of apparatus not likely to be found in a school laboratory. Nevertheless some interesting deductions may be drawn from a simple experiment with the heater described in Experiment 178.

**EXPERIMENT 180.**—To compare materials for conductivity.

This experiment, illustrated in Fig. 349, enables us to compare in a rough and ready way the rate of heat transmission through a material. The specimen, which may be a brick, slate, tile, wood, etc., is placed in position screening the aperture of the heater. The heating element having been switched on, the shutter is withdrawn and the time elapsing to the first sign of movement of the galvanometer needle recorded. Care should be taken to place the mouth of the thermopile equi-distant from the back of each specimen, and all specimens should be reduced, in the final figures, to uniform equivalent thickness, say 1-in.

The experiment should be repeated with the same specimens but with blackened surfaces, so as to eliminate the effects of differences of colour.

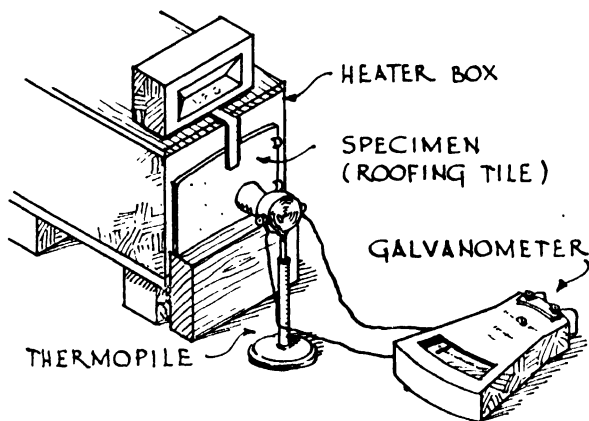


FIG. 349.—Experiment to Compare Building Materials for Thermal Conductivity.

In practical consideration of heat flow through walls, roofs, etc., materials cannot be considered singly, for they are not used singly. A wall for instance may comprise hung tiling, felt, air space (between battens), brick and mortar (in one of very many arrangements as to bond), plaster. In such cases coefficients are used by the heating specialist which apply to the type of construction as a whole, and not to the individual materials.

It will be seen from Table 21 that materials fall into fairly well defined groups according to their conductivity—firstly the metals, all good conductors—secondly other impervious materials together with the denser stones, bricks, etc.—finally the fibrous, pulverized and highly porous materials, all good insulators.

We see that to a great extent the insulating value of a material is dependent upon its porosity (see also page 72) and it is evident that this is due to the air enclosed in the material in such a way that convection is impossible. If a material such as slagwool be highly compressed, its

insulating value may be reduced by as much as two-thirds, because the proportion of entrapped air has been reduced.

It will also be clear that its insulating value will be reduced upon becoming wet, for then some at least of the pores will contain water instead of air. Study of the table will show the difference between the conductivity of water and air.

**Transmission of Heat through Roofs.**—In the case of a roof the problem is generally not so much one of conserving internal heat as of excluding external heat. Roofs are more exposed than walls, and the primary function of excluding rain is ensured with normal materials and construction, but the question of insulation from solar radiation is also of importance. As roofs, even flat roofs, are not called upon to carry appreciable loads the natural tendency is for their construction to be more flimsy than for walls and floors, and this alone renders advisable some consideration of their insulating value.

**FLAT ROOFS.**—A timber-joist type of construction, lead or copper covered, gives a fair degree of insulation because of the air enclosed between the joists, the ceiling and the outer roof boarding. When the more permanent concrete slab construction became popular several troubles, not experienced with the wood construction, became evident. Chief of these were poor insulation and excessive condensation, due to the small thickness of the slab (3-in. or 4-in.). A room immediately beneath such a roof is cold and draughty in winter and unbearably hot in summer, due to excessive heat transmission through the roof. Remedies include suspended ceilings (expensive and wasteful of capacity), and a layer of hollow tiles or filling concrete on top of the slab (additional weight, together with a risk of excessive temperature movement).

The use of a thicker slab has been shown to reduce the trouble, but this increases not only the weight of the roof but the stresses to be borne by the rest of the structure. Hollow construction is also efficient, hollow concrete beams for instance, but when other materials are introduced (*e.g.* certain types of hollow tile) insulation is not necessarily improved since such tiles may not have the same thermal capacity as the concrete.

In all such roofs the waterproofing is either a layer of asphalt or a multi-ply arrangement of bitumenized sheeting jointed in mastic, both requiring protection from direct sunshine and also perhaps from light foot traffic. Fine gravel has been largely used on ply roofs but direct on asphalt its disadvantages are obvious.

For both types of roof, thin decking tiles have proved useful in reducing the temperature of the roofing material. These are tiles of highly porous concrete faced on the upper side, as laid, with asbestos cement or similar material. The porous nature of the body of the tile

results in high resistance to conduction, whilst the light colour of the surface ensures a high degree of reflectivity of solar heat. Such tiles have been shown to maintain a temperature of the asphalt, etc. 25 per cent. below that of a similar surface exposed to full sunshine—with a corresponding decrease in temperature of the inner surface of the roof.

A coat of whitewash may increase the efficiency by as much as a further  $7\frac{1}{2}$  per cent., but to maintain this it would have to be renewed occasionally, as the following B.R.S. experiment shows. The object of the experiment was to investigate the effect of "dirt" on such tiles, and to this end the new tiles were exposed on a London roof for a period of twelve months. After six months their reflectivity was reduced to 69 per cent., and after twelve months to 50 per cent. of its original value, whereupon a washing with soap and water immediately restored it to 100 per cent.—in fact to 103 per cent., an anomaly explained by the fact that either the tiles had had some initial "dirt" or that the asbestos cement, which normally bleaches as a result of weathering in a clean atmosphere, actually did so under the accumulating "dirt."

Further experiments were made upon concrete slabs perforated and with short legs to permit a flow of air between slab and roof. These resulted in a reduction of about 26 per cent. in the temperature of the asphalt, when the slabs were left their natural colour. When the upper surface was whitened the reduction was  $27\frac{1}{2}$  per cent., but upon stopping the ventilation (without whitening) the reduction was only about 18 per cent. This last result proves that moving air disperses heat much more readily than comparatively still air, and incidentally strengthens the argument against through ventilation in 11-in. brick cavity walls.

**PITCHED ROOFS.**—Pitched roofs are normally of a totally different type of construction from flat roofs, comprising a small overall thickness of slates, tiles, sheets, etc., with, often, not even roof boarding beneath. Problems connected with such roofs are also common to sheeted walls in certain framed industrial buildings, and in all such cases the conductivity of the material is of little importance since there is such a small thickness of it. From the viewpoint of resistance to heat the two matters to be considered are :—(a) the reflectivity of the outer surface to powerful solar radiation, and (b) the emissivity of the inner surface to low-power radiation. The efficiency of different surfaces in both respects has been shown, and it follows therefore that for maximum efficiency, whatever the material, the outer surface should be white and the inner surface coated with tin or aluminium foil, or, more practicably, painted with aluminium paint.

**UNEQUAL CONDUCTIVITY.**—This concerns a practical problem which often causes much trouble. Particles of dust or soot held in suspension are carried by convection currents and deposited on surfaces on to which the currents impinge. The wall surface behind and above a heating

radiator may become soiled for this reason, but this has nothing to do with conductivity. If, however, the back of the wall is cooler than the face, heat will flow through the wall towards the cooler side and the soiling of the surface will be more marked—the greater the temperature gradient the more “dirt” will accumulate. If the wall is homogeneous the heat flow will be uniform, but if it is not, especially if of small thickness, the rate of heat flow will vary according to the conductivity of the different materials.

To take the case of a radiator placed against a thin slab or block-built partition. If the partition separates the room from a cooler corridor or other room, and the blocks have a higher coefficient of thermal conductivity than the jointing material, the face of the partition over the blocks will be maintained at a slightly lower temperature than over the joints. Over a lengthy period this will favour a greater deposition of “dirt” particles over the blocks than over the joints, and the result is that the arrangement of blocks and joints may be distinguished from the pattern formed by unequal soiling—lighter joints against a darker background. If the coefficient for the mortar is higher than that for the blocks, then the reverse will be the case and the pattern will be of darker joints against a lighter background.

Another instance of unequal conductivity, with a parallel result, is the lath and plaster ceiling. The thickness of such a ceiling is alternately solid plaster and plaster backed by lath. Conductivity between the laths is then higher than through them, and so the pattern is of light laths on a darker ground. But if metal mesh is used instead of wood lathing the pattern is reversed because the conductivity of plaster and mesh is then higher than that of plaster alone.

Although neither streaking due to convection currents nor evenly distributed soiling due to uniform conduction can be prevented, it is possible to avoid the formation of a pattern by unequal conduction. If the air behind the wall or above the ceiling could be maintained at the same temperature as that of the room no heat flow could take place. This is seldom possible, but heat loss can be greatly reduced by the use of an insulating material on the cool side of the wall or ceiling.



## FLUID PRESSURE

1. *Static Water Pressure.*
2. *Pressure of Flowing Water.*
3. *Atmospheric Pressure.*
4. *Miscellaneous Problems.*

In this chapter we are concerned mainly with problems affecting water supply and sanitation, although the principles involved apply also in some cases to the stability of buildings and other structures.

### 1. STATIC WATER PRESSURE.

As water is the most convenient liquid to use in our experiments, and as it is also the liquid with which we are most concerned in practical problems, we shall deal in this Section mainly with water, bearing in mind that the principles dealt with apply as well to all other liquids.

*All liquids at rest transmit downward pressure due to their own weight, but owing to the mobility of their particles this pressure, unlike that of a solid, is exerted also in directions other than downwards.*

#### DIRECTION OF WATER PRESSURE.

EXPERIMENT 181.—To show that water pressure acts upwards.

The apparatus comprises a glass cylinder without base and with ground rims, and a circular brass plate with a perfectly true upper surface which, when held to the ground rim, forms a watertight joint. On top of the plate is an eye to which can be attached a cord by means of which the plate may be held tightly to the cylinder.

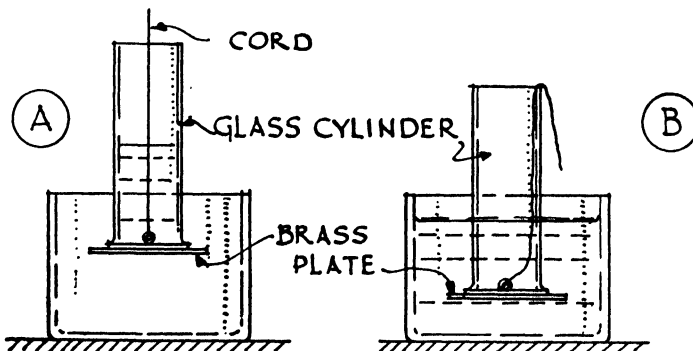


FIG. 350.—Downward and Upward Pressure of Water.

When this is done pour water into the cylinder as at A, Fig. 350. It is evident that the pull on the cord must be at least equal to the weight of the water (plus that of the plate and cord), otherwise the brass plate will be forced away and the water escape into the jar by reason of its own weight.

Now empty the cylinder, two-thirds fill the glass jar and lower the empty cylinder, with plate held in position, into it as at B. As soon as the base of the cylinder is below the water level it is found that the cord need no longer be held—the brass plate is held up by the pressure of the water acting *upwards* on its underside. This is what might be expected from a knowledge of the Principle of Archimedes.

If the brass plate in the last experiment had a small hole through its thickness it is evident that, when immersed as just described, water would spurt upwards through it into the cylinder, thus providing further proof that the water exerts pressure in an upward direction.

*At any point in a body of liquid this pressure is exerted equally not only downwards and upwards but in all directions.* This is best demonstrated in the manner illustrated in Fig. 351.

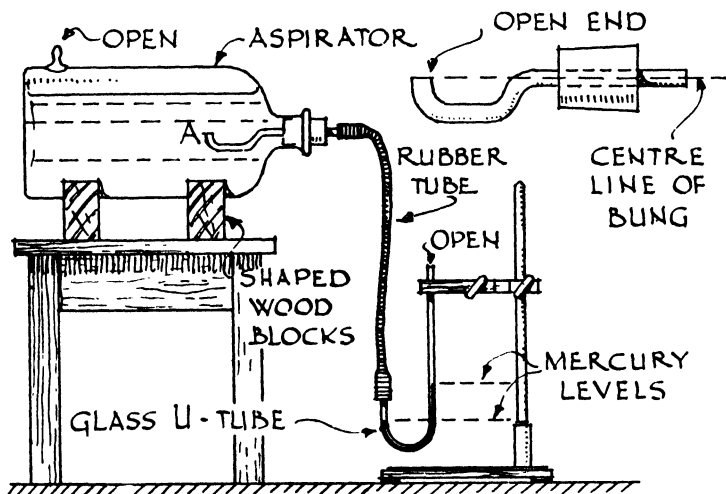


FIG. 351.—Equality of Water Pressure in all Directions at given Depth.

**EXPERIMENT 182.**—To show that the pressure exerted at any point by water, due to its own weight, is equal in all directions.

A small glass tube is bent to the shape shown and inserted through the bung of an aspirator, or other fairly wide-mouthed jar, so that it may be turned through a complete revolution whilst its open end remains at the same level A. Its other end is connected to one arm of a glass tube bent to form a U and containing a little mercury. Now as mercury and water are immiscible the water pressure exerted on the surface of the mercury in one arm of the U forces it down,

with a corresponding rise in the other arm. This mercury level is constant for a given pressure.

Now mark this level on the side of the tube and rotate the bent tube in the aspirator. No change whatever in the mercury level will be noted, showing that at point A the pressure acts in all directions with equal intensity.

**WATER FINDS ITS OWN LEVEL.**—*The free surface of a body of still water is always horizontal.* This is true whatever form the body of water may take, and is often stated "Water finds its own level." (Liquid in the pores of a solid or in a glass tube, etc. is, of course, subject to capillarity and this condition is excluded.)

**EXPERIMENT 183.**—To show that water "finds its own level."

The two aspirators shown in Fig 352 are connected by a rubber tube which is closed by a pinchcock or clip. Different quantities of water are then put into each. Whilst the cock remains closed there are two distinct bodies of water, each having its own free (upper) surface horizontal owing to the effect of gravity. Upon opening or removing the clip however, water flows from A to B until the upper surfaces coincide. This is because the whole is now a single body of water and the two surfaces are now really parts of a single free surface, the surface in contact with the outer air. (If vessel B were corked at the commencement of the experiment then the levels might not coincide since the air in B would offer resistance by exerting pressure on the surface of the water. Further, if some of the air in B were previously withdrawn level B would be higher than level A. In both cases the surface in B is *not* in contact with the outer air.

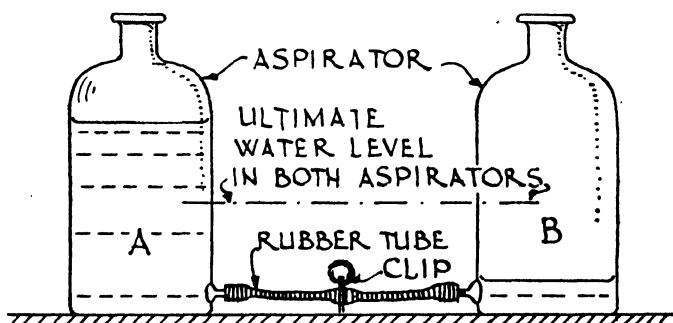


FIG. 352.—"Water finds its own Level."

**EXPERIMENT 184.**—To show that water exerts upward pressure in attempting to "find its own level."

That this is so is clear from Experiment 181, B, but the method illustrated in Fig. 353 shows it in a more striking manner. Connect a long glass tube by rubber tubing to an aspirator containing water. The water level in the tube will coincide with that in the aspirator. Now move the glass tube vertically up and down and the water level

will almost immediately adjust itself to the same general level as indicated by the dotted lines. Now seal the open end with the finger, lower the glass tube well below this level and then remove the finger. Water will issue from the open end as a fountain and, but for the friction which is great owing to the great length and small bore of the tubes, would reach the same level as in the aspirator. (Fig. 353).

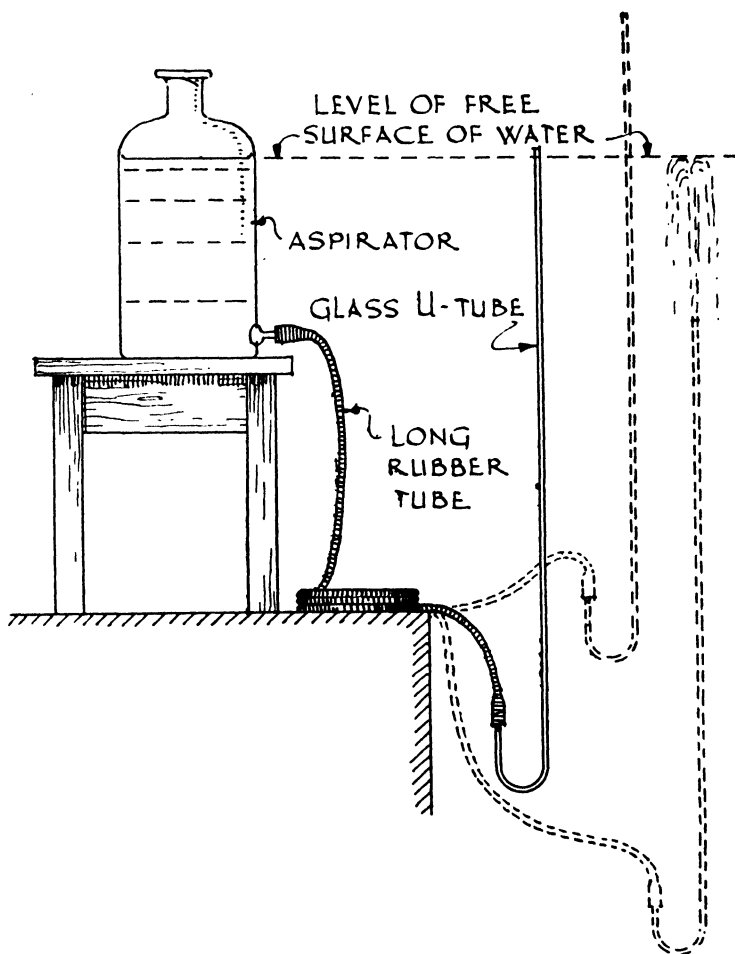


FIG. 353.—To show Upward Pressure of Water.

This is precisely what happens when an "artesian" well is sunk. Fig. 354 shows in a simple way the geological configuration which leads to the possibility of this type of well or borehole. The level to which the pocket of porous, water-bearing stratum fills is called the "water table." In the diagram two possible levels are shown, A and B. In the case of A a well sunk into the porous stratum would result in a "gusher"

but for the fact that the supply obtained is controlled. It is evident, however, that there is a useful pressure behind the water at the control tap. In the case of B the water again finds its own level (this time below ground level) from which it must be raised by pumping. This is the more usual type.

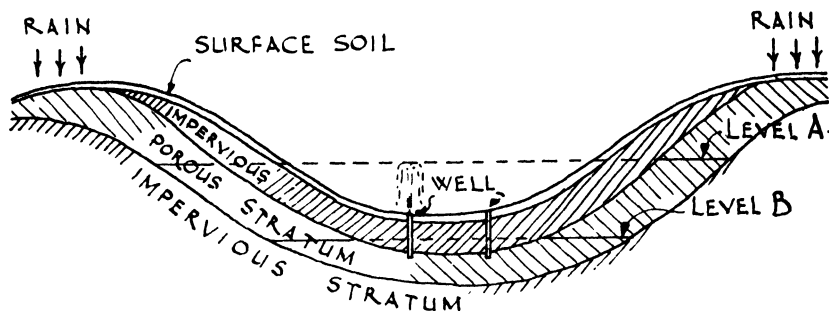


FIG. 354.—The Artesian Well.

A further illustration of this principle is the water supply of a district served by gravity from a service reservoir. A service reservoir may be a large tank at ground level on high ground, or elevated as a water tower on low ground. It should not be confused with an impounding or a storage reservoir—several service reservoirs may be fed by one of these. The reservoir, the mains, and the pipes in the buildings all comprise a single body of water (assuming all control valves to be open). Any tap which is at a lower level than the free surface of the reservoir, such as those shown in Fig. 355, will give a supply.

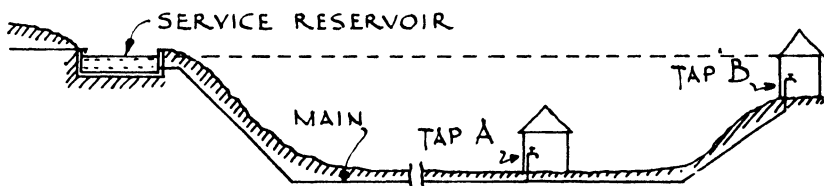


FIG. 355.—Pressure of Water at Taps due to Head.

**INTENSITY OF WATER PRESSURE.**—*The pressure at any point in a body of liquid increases with the depth below the free surface.*

**EXPERIMENT 185.**—To show the difference in pressure at different depths.

Take a U-tube with one long arm and place mercury in the bend. The two mercury levels will coincide as the mercury finds its own level. Now immerse the bend in water and slowly submerge it deeper and deeper, watching the levels carefully. It will be seen that the deeper the tube is submerged the greater is the difference between the two levels, that at A (Fig. 356) being depressed and that at B raised. This is due to the downward pressure of the water on the surface of the mercury at A.

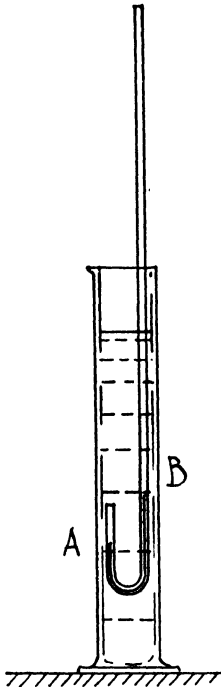


FIG. 356.—Showing Increase of Water Pressure with Depth.

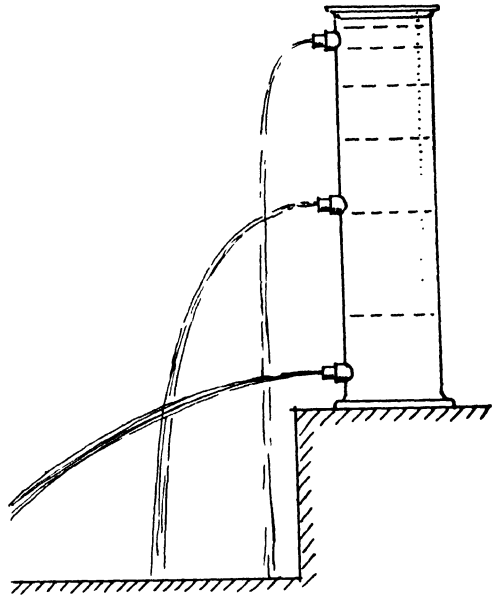


FIG. 357.—The Pressure Jar.

This difference in pressure may also be shown by means of the "pressure jar" shown in Fig. 357.

#### EXPERIMENT 186.

The pressure jar is a tall glass cylinder having three outlets in the side arranged in a vertical row. Each has a rubber bung through which passes a small hole, all being of the same diameter and plugged by a match.

Fill the jar with water and remove the three plugs simultaneously. The water will issue from the holes as shown. This proves that at each point pressure is acting horizontally and that this pressure is greater the greater the depth, since the water is expelled with the least force from the topmost hole and with the greatest force from the lowest hole.

**WATER PRESSURE DUE TO HEAD ONLY.**—The vertical height from any point in the liquid up to the free surface is called the *head* of liquid causing the pressure at that point.

*The pressure at any point in a body of liquid increases proportionally with the head. Thus, at twice the depth the pressure is doubled, and so on. The volume of liquid above the point is immaterial.*

**EXPERIMENT 187.**—To show that pressure increases directly as the head, and not as the volume, of liquid.

The apparatus required is shown in Fig. 358. Having filled the aspirator open the tap and fit the mercury U tube to the rubber tube so that the water is in contact with the mercury. Fix the rule vertically, in a stand or in any other convenient way, and hold the U-tube so that mercury level A is 1-ft. below the water level (the top of the rule). This gives a head of 1-ft. (H). Now read off the

difference in mercury levels ( $h$ ), .88-in. Now lower the U-tube so as to give a head H of 2-ft. The difference  $h$  will now be 1.76-in. Repeat with  $H = 3$ -ft. when  $h$  will be about 2.65-in. If a graph be drawn to show this relationship it will be found to be a straight line.

To show that the pressure does not depend upon the volume of water, close the tap, disconnect the rubber tube adjacent to it and raise it to the same level as that of the water in the aspirator, taking care not to lose any of the water from the tube. Now arrange the U-tube to give one or more of the heads as before and the readings  $h$  will be found to be unaltered, although the quantity of water producing the pressure is now very much less than before. As further proof raise the end of the rubber tube to a point considerably higher than the aspirator water level. The pressure as registered by the mercury is now considerably greater than when using the aspirator full of water.

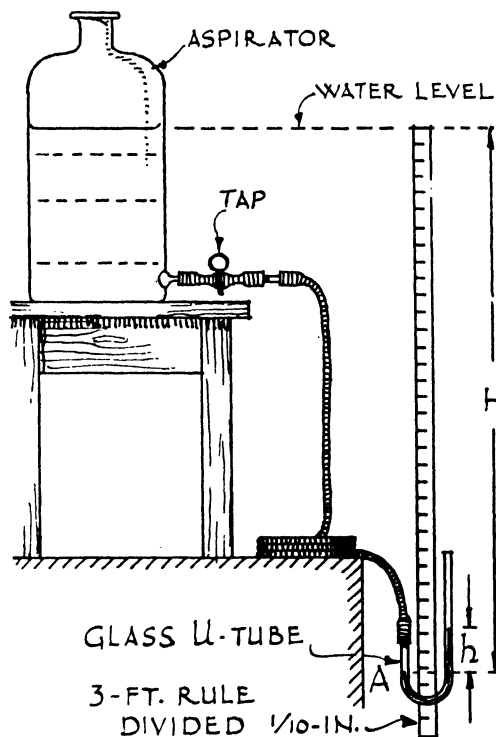


FIG. 358.—To show that Water Pressure increases directly as the Head—irrespective of Volume.

**WATER PRESSURE ON SOLID SURFACES.**—It is thus possible to create a very great pressure by the use of only a small quantity of water. Consider Fig. 359 which shows vessels of different shapes and capacities, but each having the same area of base and filled with water to the same height. The pressure on the base of vessel A is due to the weight of the whole volume of water, but only because the sides are vertical. *The pressure of a liquid on a bounding surface is always normal to the surface.* In vessels A, B and C, therefore, the pressure on the sides is horizontal. In the case of vessel A this is indicated by arrows, whilst other arrows indicate

the vertical pressure on the base. Now, there being no other vertical pressure, the pressure on the base is due to the whole volume of water.

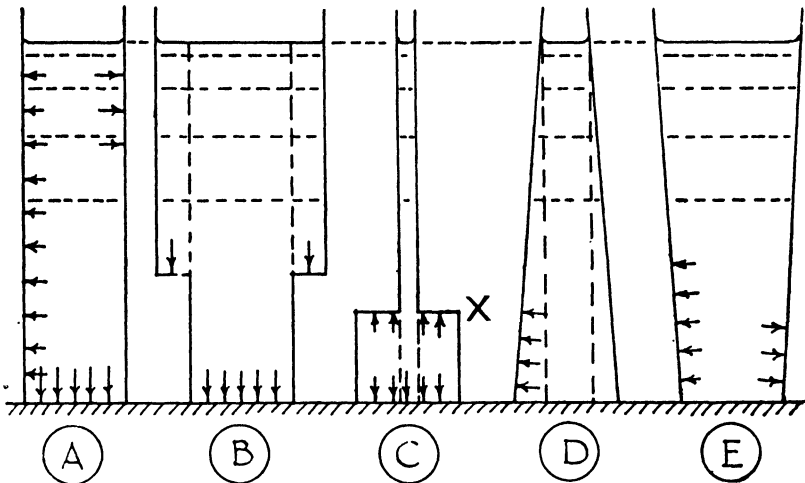


FIG. 359.—Effect of Shape of Vessel upon Pressure on Base.

In vessel B the vertical pressure is shown, that acting on the base being clearly as before, and equally clearly caused only by the water enclosed by the vertical dotted lines, a volume equal to that in vessel A.

In vessel C, which is really a low, closed vessel having a vertical tube rising from the top, the pressure at level *x* acts upwards on the underside of the "top." This top is therefore reacting downwards (the force being transmitted through the water—see page 421) and the pressure on the base is thus the same as in the vessels previously considered.

In vessels D and E too the pressures on the bases are as before ; in D the extra pressure is transmitted to the base via the sloping side (as in C but in this case due to the vertical components of the oblique pressures), whilst in E the pressure from the water not vertically over the line is similarly exerted on the sides.

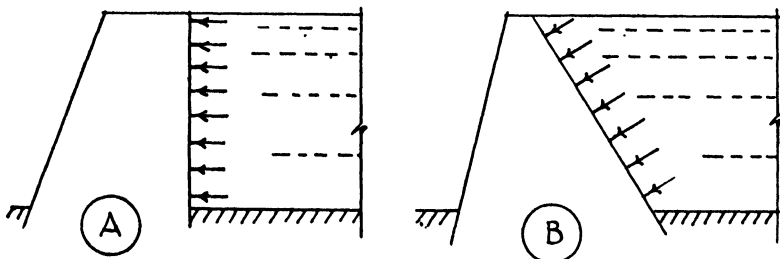


FIG. 360.—Showing that Water Pressure is Normal to the Bounding Surface.



When a masonry or mass wall is built to retain water it is an advantage if the face in contact with the water is battered (as at B, Fig. 360) rather than vertical (as at A), because then the thrust from the water is inclined downwards instead of being horizontal, and the moment of this thrust has to be countered by that of the downward force due to the mass of the wall.

**WATER SUPPLY PROBLEMS.**—Referring to Fig. 355 it will be now clear that the pressure at tap A is greater than that at tap B because of the greater head of water. The reason for the service reservoir will now be appreciated—the main storage reservoir, a natural or artificial lake on high ground perhaps many miles away, may be such as would give too great a head, with excessive pressure on the mains and pipes, especially in the low-lying parts of the district. Further, one main reservoir may serve many districts at various altitudes, and each service reservoir thus regulates the maximum pressure in its own district by keeping it within working limits.

In some districts the water supply is not from water impounded on high ground but is pumped from rivers or boreholes. Although in such cases the pressure in the mains may be maintained by continuous pumping, the water is more usually pumped up to service reservoirs or tanks so that it may flow thence by gravity under a suitable head.

The same principle is at work in the case of taps which are not supplied direct from the mains. Here the cold water supply cistern functions in regard to the building in the same way as does the service reservoir in regard to the district. It is fixed in a high part of the building (see Fig. 361) and is supplied through an automatic ball tap (see page 444) via a service pipe—underground to the building—and a rising main—inside the building. There is no contact between the water in the cistern and that in the mains—they are distinct bodies of water—and the head

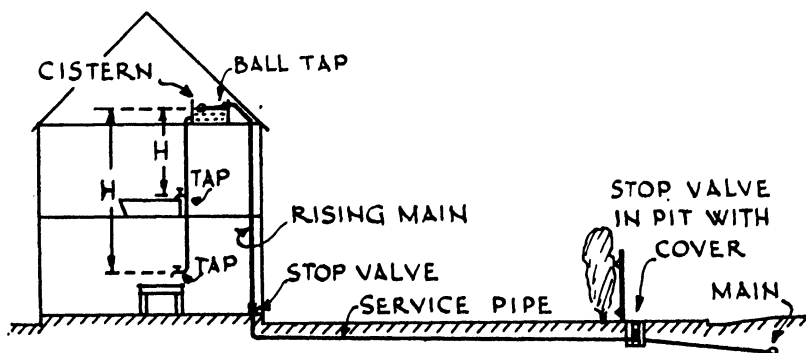


FIG. 361.—Pressure of Water at Fittings served by Cistern.

producing the pressure at any tap is then due only to the height of the free surface in the cistern above the tap ( $H$  in Fig. 361).

**VARIATION OF PRESSURE WITH DENSITY.**—The laws governing pressure in a liquid apply to all liquids but as the pressure is due to the weight of the liquid it obviously depends upon the density of the liquid. Thus in Experiment 184 the water in the glass tube rose to the same height as that in the aspirator. On the other hand the mercury used in Experiment 187 rose only a fraction of this amount, because mercury is denser than water. In that experiment the column of mercury  $h$ -in. high is held up or balanced by a column of water  $H$ -in. high.  $\frac{H}{h}$  therefore represents the ratio between the density of the mercury to that of the water, in other words the specific gravity of the mercury. (13.6).

We may therefore say :—*The pressure at any point in a body of liquid varies directly as the density of the liquid.*

**USE OF U-TUBE TO FIND SPECIFIC GRAVITY.**—From the preceding paragraph it is clear that we could use the apparatus in Fig. 358 to determine the specific gravity of any liquid (which does not mix with water) by substituting the liquid for the mercury in the U tube and measuring  $H$  and  $h$ . It is more convenient, though, to contain the water in a tube, and so the simplest arrangement is a tall U-tube, mounted on a stand and with a sliding rule to enable  $H$  and  $h$  to be read off quickly and accurately. This is illustrated in Fig. 362.

**EXPERIMENT 188.**—To determine the S.G. of paraffin by the U-tube method.

Using a small glass funnel, pour water into one arm of the tube so that it rises 6-in. or so up each side of the bend. Then pour paraffin down the other arm in any quantity so that the water level in the same arm remains on the straight part of the tube. Now slide the scale (which may be in inches, centimetres, or any other equal divisions) until zero coincides with the mark of separation, and read off the height above this mark of the water ( $H$ ) and the paraffin ( $h$ ).

Add further water and/or paraffin so as to obtain a series of readings, and set down the results as a table. The taller the columns of the two liquids the more accurate the result, since experimental error is then reduced.

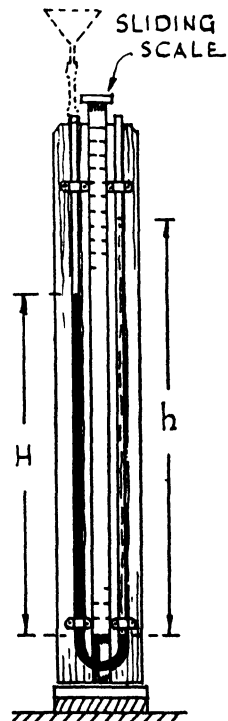


FIG. 362.—S.G. of Non-Miscible Liquid by U-Tube.

Following are actual results for paraffin and water :—

Ht. of water	Ht. of paraffin	S.G.
$H$	$h$	$\frac{H}{h}$
10.5-in.	12.5-in.	.84
20-in.	23.8-in.	.85
27.2-in.	32-in.	.85

Mercury may be used in place of water as the standard liquid provided that its known S.G. of 13.6 is taken into account in making the calculation. The advantage of this is that it does not mix with many liquids which do mix readily with water, but it has a disadvantage in that the comparatively short column of mercury is more difficult to measure accurately. A better method, for a liquid which mixes with water, is given in Experiment 194, page 430.

All these forms of U tube, used for measuring or comparing pressures, are called *U-gauges* or *manometers* and from Experiment 187 it is obvious that the diameter of the bore of the tube does not affect their accuracy so long as it is uniform.

**THE WATER U-GAUGE.**—For low pressures water is a convenient liquid to use, as in the gas-fitters' water gauge. This is shown in Fig. 363 and comprises a glass U tube mounted in a metal case for protection when carried in a tool bag or pocket. Both ends are open but one end has a brass nipple to take the end of a rubber tube leading to the pipe to be tested. The scale is marked as shown and under no pressure both water levels are at zero on the scale. In use a cock with a nipple is fitted to the pipe and a length of rubber tubing connects this to the gauge. Upon opening the cock the gas exerts its pressure on the water in the gauge, depressing the level in one arm and forcing it up in the other. The new levels, as shown, indicates a pressure of "2 inches of water column." Gas installation pressures are referred to in these units instead of in lb. per sq. in., but one inch of water column is the equivalent of .0362-lb. per sq. in.

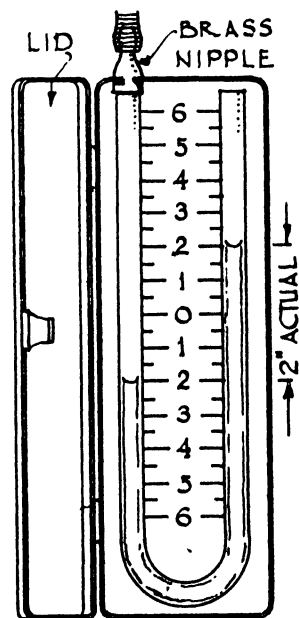


FIG. 363.—Gasfitters' Water Gauge.

The water gauge is also used for testing the soundness of a new installation before connecting the gas supply, in which case air is blown

into the pipes, the gauge indicating any subsequent drop in pressure due to leaky joints or pipes.

**WATER PRESSURE CALCULATIONS.**—Fig. 364 shows a tank whose internal dimensions are 1-ft.  $\times$  1-ft.  $\times$  such height that a depth of 1-ft. of water may be accommodated.

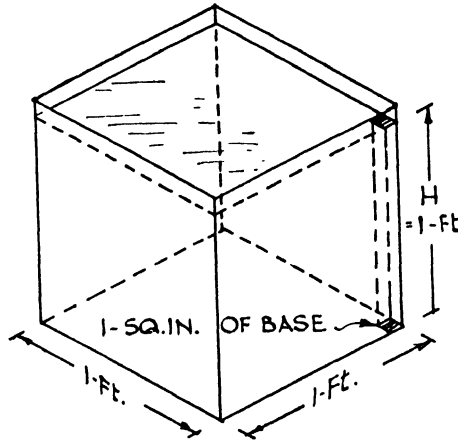


FIG. 364.—Intensity of Water Pressure according to Head.

Then the total pressure on the base of the tank = the total weight of water, and if we call the total pressure  $P$

$$\begin{aligned}\text{Then } P &= \text{Volume of water} \times \text{Density} \\ &= 1\text{-c.ft.} \times 62\cdot43\text{-lb. per c.ft.} \\ &= 62\cdot43\text{-lb.}\end{aligned}$$

This is the pressure per sq. ft. of base for a head of 1-ft. and the pressure per sq. in. of base =  $\frac{62\cdot43}{144} = \cdot434\text{-lb. for 1-ft. head.}$  As the pressure increases uniformly with the head, then the pressure for any head is equal to 62·43-lb. per sq. ft. or ·434-lb. per sq. in. *per ft. of head.* (Equivalent to 5·202-lb. per sq. ft. or ·0362-lb. per sq. in. *per inch of head.*)

The pressure *per unit of area* (sq. ft., sq. in., sq. cm., etc.) is strictly called the *intensity of pressure* ( $p$ ), whilst the pressure acting on a given area is as already stated the *total pressure* ( $P$ ). Thus :—

$$\text{Total pressure} = \text{Intensity of pressure} \times \text{Area}$$

$$\text{or } P = p \times A$$

$$\text{Similarly } p = \frac{P}{A}$$

$$\text{and } A = \frac{P}{p} \text{ exactly as for simple stress (see Chapter XIV).}$$

When we speak of *pressure* we mean *intensity of pressure* and in referring to the *amount of pressure on a given area* we call it *total pressure*. An intensity of pressure of 1-lb. per sq. in. acting on an area of 10 sq. in. therefore means that a total pressure of 10-lb. is acting *at the rate of* 1-lb. per sq. in., and it is important to realize that pressure may act at this intensity on an area less than 1 sq. in. Thus a total pressure of  $\frac{1}{2}$ -lb. acts on an area of  $\frac{1}{2}$  sq. in. with an intensity of 1-lb. per sq. in.

British units are invariably used in all water pressure problems as such problems are always closely related to practice.

**EXAMPLE.**—A cold water tap, such as is shown in Fig. 355, is 54-ft. vertically below the level of the water in the service reservoir. What is the pressure on the tap ?

The head of water acting is 54-ft. and the pressure  $p$  is .434-lb. per sq. in. per ft. of head =  $.434 \times 54 = \underline{23.43\text{-lb. per sq. in.}}$  *Ans.*

**EXAMPLE.**—The tap mentioned is of the screw-down type and the internal diameter of the seating is  $\frac{1}{2}$ -in. What is the total upward thrust on the washer when the tap is closed ?

Area of washer, etc. exposed to pressure =  $\pi \frac{D^2}{4} = .0196$  sq. in.

And total pressure =  $p \times A = 23.43 \times .0196 = \underline{4.6\text{-lb.}}$  *Ans.*

When a liquid other than water is involved it is usually most convenient to calculate for water and subsequently take into account the different specific gravity of the liquid.

**EXAMPLE.**—A drum 1-ft. in diameter contains 15 gallons of oil (S.G. = .82). What is the pressure on the base of the drum ?

Volume equivalent to 1 gallon = .16 c.ft.

“ “ “ 15 “ =  $.16 \times 15 = 2.4$  c.ft.

Diameter of drum = 1-ft.

Area of base =  $\pi \frac{D^2}{4} = .7854$  sq. ft.

Therefore height of drum =  $\frac{2.4}{.7854} = 3.05\text{-ft.}$   
(Head of oil)

$p$  due to 3.05-ft. head of water =  $3.05 \times .434\text{-lb. sq. in.}$

$p$  due to oil =  $3.05 \times .434 \times .82 = \underline{1.08\text{-lb. sq. in.}}$  *Ans.*

**WATER PRESSURE ON FLOORS AND WALLS.**—When the floor of a building is at a depth below ground water level some of the ground water is displaced, and in tending to find its own level it exerts upward pressure on the underside of the floor and inward pressure on the outside of the walls. Such construction must therefore be able to withstand not only the percolation of water but mechanical pressure (with the resulting stresses) due to a head of water, and this may be very considerable.

**EXAMPLE.**—A heating chamber is below ground level and ground water rises to a maximum height above the underside of the floor concrete of 3-ft. The area of the floor is 400 sq. ft. What is the effect upon the floor and walls ?

Pressure due to 1-ft. head = 62.43-lb. per sq. ft.

" " " 3-ft. " = 187.3-lb. per sq. ft.

Total pressure =  $187.3 \times 400 = 74,916$ -lb.

=  $33\frac{1}{2}$  tons, nearly. *Ans.*

This pressure is spread uniformly over the floor area, acting upwards. The walls are subjected to a horizontal pressure, maximum at floor level and equal to that on the floor, decreasing uniformly to zero at water level. The nature of these pressures can best be shown diagrammatically as in Fig. 365.

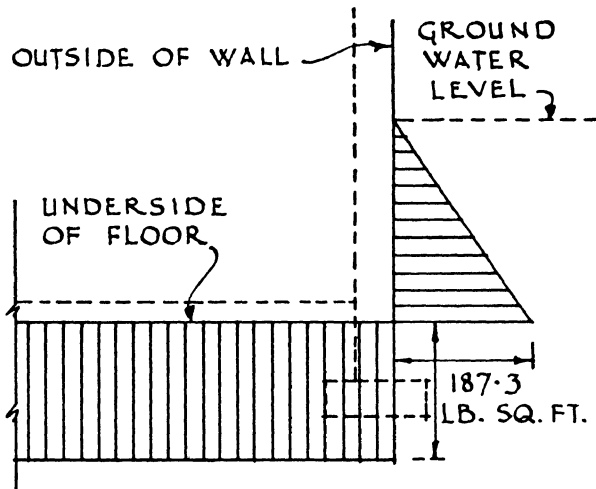


FIG. 365.—Pressure of Water on Floor and Walls of Basement.

**TESTING OF DRAINS.**—When an underground drain becomes blocked it fills up to the level of an inlet gulley before the trouble is apparent. The drain pipes in an ordinary system, especially if of "tested" quality, are usually capable of withstanding such internal pressure ; it is the joints which are liable to fail and so produce a leaky drain, a serious menace to health because the ground then becomes fouled. As the lengths and gradients of drains differ widely the actual pressure developed varies, but every new drain should obviously be capable of standing up to a pressure somewhat higher than that which could occur accidentally in this way.

The "water test" is designed to submit the drain to a certain maximum pressure by arranging a given head of water. A system of

drains comprises a number of straight lengths of drain between chambers ; it may therefore be tested in separate lengths so that any fault may be localized.

The test is carried out by plugging the lower end of the drain where it enters an inspection chamber and then filling with water, any subsidence being evidence of a leak. Two types of drain plug are illustrated in Fig. 366, the pneumatic plug at A and the expanding ring plug at B, both kinds being made to suit drains of different diameters.

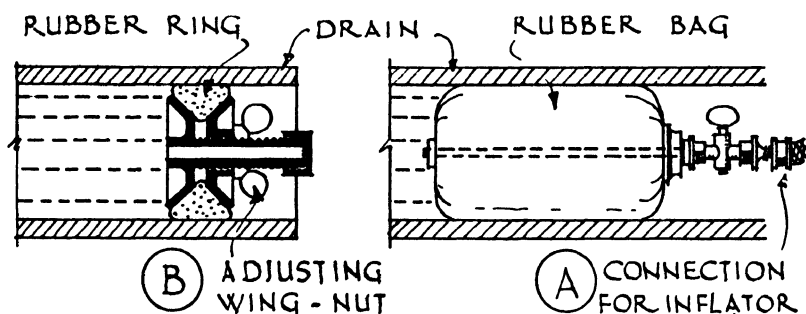


FIG. 366.—Drain Plugs for use in Water Test.

In order to increase the head it is necessary to fix temporarily a vertical pipe at the head of the drain. In the case of the highest length of drain the head of the drain is probably a gulley trap and a loose drain pipe may be stood vertically in the gulley and sealed around its base with clay. For other lengths the head of the drain is in an inspection chamber and the increased head of water is best obtained by plugging the head of the drain and connecting through it a stout rubber tube and vertical iron pipe, which may then be filled to the required height. Otherwise the higher chamber itself is filled sufficiently to give the required head of water. In this case the foot of the upper length of drain must be plugged, and also some time must be allowed to elapse before assuming that subsidence means a leak, because the walls of the chamber are porous and absorb a certain amount of the water.

In this way each length of drain is subjected to a specified maximum pressure, but it is better to test the whole system together to a pressure a little higher than the maximum that could occur by accident. This would mean that a small system having a small total fall is not tested so severely as would be a more extensive system, and this is certainly a more logical procedure. Should the drain prove to be faulty it could then be tested in sections merely to localize the fault.

New drains are of course tested as described before filling in the trenches, and it is a simple matter to remedy the fault. Old drains are buried, however, and the leak must preferably be located to within a foot or two in order to reduce labour in excavating, etc. This is done by partly inflating the pneumatic plug on the end of a long "connection" and floating it along the drain, stopping every few feet to complete the inflation and test as described.

If it is desired to know with exactitude the amount of pressure applied, a mercury gauge may be connected to the lower plug. Some local authorities are satisfied with an "air pressure" test on drains. This is totally different in principle to the water test and is not adequate for new drains. It is described on page 436.

PRINCIPLE OF THE HYDRAULIC MACHINE.—It has been shown, page 412, that the pressure from a liquid is always perpendicular or normal to the bounding surface. As liquids are to all intents and purposes incompressible it follows that *when additional pressure is applied to a body of liquid this force is transmitted through the liquid and exerted at the same intensity on all bounding surfaces in directions normal to those surfaces.* This is sometimes called the *principle of the transmission of fluid pressure.*

Suppose we have a body of water contained in a syringe, a tube of equal diameter fitted with a plunger or piston, and a rubber tube connecting the two. If we thrust on the syringe plunger with any force, say 1-lb., this force will be transmitted through the water and exerted on the sides of the tubes and on the second plunger. The intensity of pressure will be equal throughout, and on the second plunger, this being equal in surface area to that of the first, the total pressure will be 1-lb. If the area of the second plunger were half, then the total pressure on it would be  $\frac{1}{2}$ -lb., and if it were twice, then the total pressure on it would be 2-lb., or *more than the applied force.* This is evident from the fact that  $P = p \times A$ , and may be proved as follows :—

#### EXPERIMENT 189.

The apparatus consists of two brass cylinders standing vertically on a baseboard and connected near their bases by a small diameter tube. Their diameters are such as to give sectional areas in the proportion of 1 : 2. Each contains a plunger and vertical rod ending in a tray or pan, and is fitted with a cap or lid with a hole which accommodates and acts as a guide for the rod.

The plungers, etc., are removed, a small quantity of water introduced, and the plungers replaced so that no air is contained—*i.e.* so that the plungers are in direct contact with the water. Press down on both pans and adjust until both are level, then place a weight on the pan of the smaller cylinder. The apparatus acts somewhat like a pair of scales, this pan going down and the other rising. To maintain a balance it is found that the weight to be put on the second pan must be exactly twice the value of the first.



Let us assume that the plungers are 1 sq. in. and 2 sq. in. in area respectively. Upon placing a weight of .5-lb. on the smaller one we impart this total pressure to the water immediately beneath this plunger, and as the area affected is 1 sq. in. then the pressure  $p = \frac{P}{A} = \frac{.5}{1} = .5$ -lb. per sq. in. This pressure is transmitted through the water and exerted *at the same intensity* on all bounding surfaces *including the underside of the larger plunger*. Here, therefore, the total pressure  $P = p \times A$  or  $.5 \times 2 = 1$ -lb. If the second plunger had been 1,000 sq. in. in area the weight supported by it would be 500-lb., and so on.

This is the principle upon which all hydraulic machines work, lifts, presses, etc., but as in the testing machine shown in Fig. 157, page 208, the pressure is applied and built up by pump. If the apparatus shown in Fig. 367 be considered as a machine it will be seen that the mechanical advantage is obtained with a corresponding velocity ratio, as in other machines.

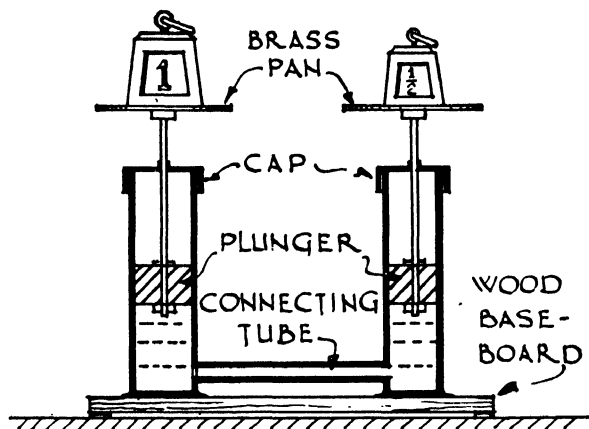


FIG. 367.—Principle of Hydraulic Machinery.

**WATER PRESSURE AND STABILITY OF STRUCTURES.**—Before leaving the subject of static water pressure we may refer briefly to some instances in which it is of importance in connection with the actual stability of a structure.

A dam is a structure built to impound water in a valley for the purpose of a large scale water supply scheme. Fundamentally it is like the wall of the heating chamber in the example on page 419, but the head of water would be very much greater. The terrific pressures resulting from such heads are resisted by the dam according to its design—some are built in reinforced concrete and designed to resist the shearing and bending stresses set up, others rely merely on their mass and are of

masonry, masonry and earth, or mass concrete. In all such cases the retention of the water presents no difficulty to the engineer, but the effects of seepage of water under high pressure cannot always be foreseen and many dam failures have been shown to be due to this. Although the dam satisfactorily withstands the lateral pressure, failure is caused by upward pressure over its base literally floating it away.

If a large building has to be erected on a riverside or similar site the foundation problem is often difficult owing to the fact that the soil may be soft mud to a considerable depth. One method adopted in such cases is to prevent lateral escape of the soil by enclosing it within a "ring-fence" consisting of a retaining wall or sheet piling, and to cover the enclosed area with a concrete raft on which the building is placed. Advantage is thus taken of the high bearing power of semi-liquid mud, when efficiently confined, due to the incompressibility of the water. Some Thames-side buildings are supported in this way.

## 2. PRESSURE OF FLOWING WATER.

When water is flowing through a pipe the pressure at any point is less than when the water is still; in fact if the velocity of the water is great enough there is practically no pressure at all, as in the case of a column of water after ejection from a nozzle. From this it may be inferred that the pressure on the inner surface of the pipe decreases with increase of velocity; this can easily be proved to be so.

**EXPERIMENT 190.**—To show the drop in pressure when water in a pipe commences to flow.

Fit up the apparatus shown in Fig. 368, run water into the aspirator and tubes, then close cock A and allow the aspirator to become nearly full. Now with chalk mark the water level on the aspirator and the two vertical tubes. This is a case of water finding its own level, and the vertical tubes are used for recording the pressure in height of water column at the points B and C in the horizontal tube.

Now open slightly cock A and by manipulation of the supply tap keep the water level in the aspirator constant at the chalk mark. The water level in tube B will fall slightly and that in tube C will fall lower still. Upon opening cock A a little more both levels will fall further, and upon opening it fully the water levels will take up fixed positions lower still. The supply must throughout be regulated to keep the water level in the aspirator on the mark.

If desired, the actual loss of pressure in this experiment may be calculated. Assuming that the column in tube B is lowered by 3-in. and that in tube C by 4-in. then, at the rate of  $\cdot 434$ -lb. per sq. in. per ft. head, this represents a reduction in pressure at point B of  $\cdot 108$ -lb. per sq. in. and at point C of  $\cdot 145$ -lb. per sq. in. Alternatively, if the head  $H$  and also the heights of the water columns be measured, the actual pressures at these points may be found.

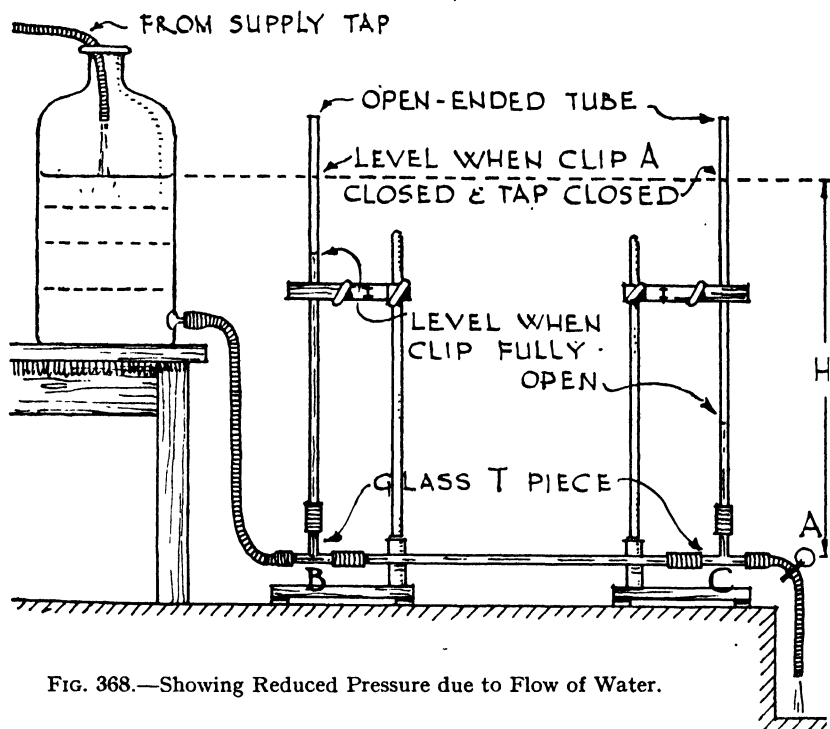


FIG. 368.—Showing Reduced Pressure due to Flow of Water.

There are two reasons for this loss of pressure. In gaining its initial velocity from rest, the energy due to its weight causing it to fall to the lower pipe is partly absorbed. Friction between the water and the inside of the tube also absorbs some of the energy, even in a straight, smooth bore, whilst obstructions, bends, etc. absorb more still.

When a pipe is constricted or reduced in diameter *at some point* the velocity of the flow, if the bore is running full, is increased at this point and the pressure consequently reduced. This is seen in the case of a laboratory sink tap or a hose pipe fitted with a reducing nozzle, where the taper of the nozzle results in a more powerful jet being obtained. Again, the slight constriction at the top of a smoke flue caused by the fitting of a chimney pot gives an increased updraught.

**FLOW OF WATER IN DRAINS.**—When water is flowing by gravity through a straight, smooth pipe (not vertical) its velocity depends upon two things, viz. the inclination of the pipe, and the amount of water passing through the pipe.

The degree of inclination to the horizontal is called the *fall* or *gradient*, and for a drain is made as slight as possible to avoid unnecessary excavation and undue wear on the pipe from too high a velocity. As the fall of drains and similar pipes is usually very slight it is not expressed in

degrees but as a ratio of vertical distance to sloping distance, or drop to length of drain. If we imagine this as represented by a triangle then the horizontal distance is its base, the length of drain its hypotenuse, and the drop its perpendicular; the ratio drop to length is then  $\frac{\text{perpendicular}}{\text{hypotenuse}}$  which is the *sine* of the angle of inclination. In practice a drop of unity is taken, and the fall is thus expressed as "1 in 20," "1 in 50," etc., the sine of the inclination then being  $\frac{1}{\text{length}}$ .

The amount of water passing through the pipe obviously affects the velocity, as also does the shape of the pipe's cross-section, because for a given fall and quantity of water the amount of friction is governed by the extent to which the bore of the pipe is in contact with the water. A drain is said to be flowing  $\frac{1}{4}$  full,  $\frac{3}{4}$  full, etc. when it is full to  $\frac{1}{4}$ ,  $\frac{3}{4}$ , etc. of the *height* of the cross-section, not  $\frac{1}{4}$ ,  $\frac{3}{4}$ , etc. of the *area*. In a cross-section of the drain the quantity of water is represented by the cross-sectional area of the flow, and the surface in contact with the pipe is represented by the length of wetted perimeter (see Fig. 369). The ratio of flow area to wet perimeter for any pipe under any condition is called its *hydraulic mean depth* (H.M.D.) and for any given pipe it varies according to the amount of the flow—whether  $\frac{1}{4}$ ,  $\frac{1}{2}$  full, etc.

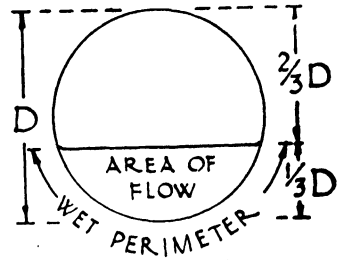


FIG. 369.—H.M.D. of Circular Pipe.

Where A = Area of flow

and P = Length of wet perimeter,

Then H.M.D. =  $\frac{A}{P}$  and for a circular section with different flows

its value in terms of diameter (D) is as given in Table 22.

TABLE 22.

H.M.D. of Circular Drain Flowing					
$\frac{1}{4}$ FULL	..	..	..	..	.186 D
$\frac{1}{2}$ FULL	..	..	..	..	.25 D
$\frac{3}{4}$ FULL	..	..	..	..	.291 D
FULL	.	..	..	..	.25 D

The formula used in calculations for velocity, fall, etc., is:—

Where  $V$  = Velocity of flow (ft. per second).

H.M.D. = Hydraulic Mean Depth (ft.).

$$S = \text{Sine of inclination} \left( \frac{1}{\text{length}} \right)$$

$$\text{Then } V = 100\sqrt{\text{H.M.D.} \times S}$$

$$\text{Or } S = \left( \frac{V}{100} \right)^2 \div \text{H.M.D.}$$

and from this:—

$$\text{Length} = \frac{1 \times \text{H.M.D.}}{\left( \frac{V}{100} \right)^2} = \frac{10,000 \times \text{H.M.D.}}{V^2}$$

The minimum velocity of flow through a foul drain to ensure self-cleansing is from 4 to 6 ft. per second.

EXAMPLE.—Determine the fall required for a 4-in. foul drain to produce a velocity of  $4\frac{1}{2}$ -ft. per second when flowing full

$$\begin{aligned} \text{Length} &= \frac{10,000 \times \text{H.M.D.}}{V^2} \\ &= \frac{10,000 \times .25 \times 4}{4.5 \times 4.5 \times 12} \\ &= 41\text{-ft.} \end{aligned}$$

The fall is therefore 1 in 41.

EXAMPLE.—A 6-in. drain is laid to a fall of 1 in 60. What is the velocity of flow when running one-third full?

$$\begin{aligned} V &= 100 \sqrt{\text{H.M.D.} \times S} \\ &= 100 \times \sqrt{.186 \times \frac{1}{60}} \\ &= \underline{5.5\text{-ft. per second.}} \end{aligned}$$

### 3. ATMOSPHERIC PRESSURE.

The atmosphere is held to the earth by gravity, its density being .00129 gm. per c.cm. or 1.29 oz. per c.ft. (at a temperature of 0 deg. Cent. and a pressure of 30-in. of mercury—see page 428). Its density may be obtained approximately in the following manner.

EXPERIMENT 191.—To determine the density of atmospheric air.

Take a round-bottomed flask fitted with short glass and rubber tubes as in Fig. 317, page 364, and put into it a small quantity of water. Boil the water and when steam issues from the rubber tube apply a pinchcock or clip and quickly remove the Bunsen. Allow to cool, when the steam in the flask will condense leaving a fairly good vacuum.

Now weigh the flask and the remaining water, open, but do not remove, the clip so as to admit air, and re-weigh. The weight of

the enclosed air can now be obtained by subtraction. To find its volume pour the water into a graduated cylinder and note the reading; then fill the flask with water up to the level of the clip, pour this into a cylinder and note its volume. The volume of the air can now be found by subtraction.

Having found the weight and volume of the air enclosed in the flask we can readily find its density. Following are experimental figures :—

Weight of flask before admitting air	=	62.59 gm.
"    "    "    after    "    "	=	62.713 gm.
"    "    air	=	62.713 - 62.59 = .123 gm.
Volume of original water	=	21.2 c.cm.
"    "    water up to clip	=	116.4 c.cm.
"    "    air	=	116.4 - 21.2 = 95.2 c.cm.
Density of air	=	$\frac{.123}{95.2}$ = .00129 gm. per c.cm.

The density of the air is not uniform, it varies with altitude being denser near to the earth's surface and becoming less dense as the height increases. Since air is a gas, its density varies also both with temperature and pressure. The experimental result may differ from the figure stated not only because of experimental error but because under the conditions of such an experiment the temperature and pressure of the air are extremely unlikely to be those stated.

Like liquid pressure the pressure of the atmosphere is exerted in all directions.

**EXPERIMENT 192.**—To show that the atmosphere exerts upward pressure.

Half fill a gas jar with water, place a sheet of thin card on top and holding it firmly to the mouth of the jar quickly invert the jar. It is now possible to remove the hand from the card, the card being held in position by upward pressure of the air in spite of the fact that the water within the jar is pressing downwards on it.

Repeat the experiment with the jar completely full of water as in Fig. 370. Again the card is held securely in position by air pressure. The experiment would still be possible if a much deeper jar were obtainable, in fact not until the jar were about 34 feet deep would the card be forced away by the downward pressure of this column of water exceeding the upward pressure.

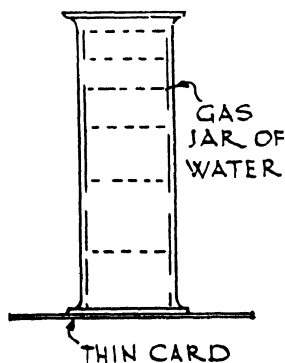


FIG. 370.—Upward Pressure of the Atmosphere.

This last statement, fantastic though it might appear in connection with this experiment, can easily be proved in a slightly different way. (See next experiment.)

**Measurement of Atmospheric Pressure.**—The pressure of the atmosphere may be measured by balancing it against a column of liquid of known density. This was first done by Torricelli, an Italian scientist, in 1643, using mercury as the liquid. The apparatus is as used in Experiment 169, page 375, and shown again in Fig. 371.

**EXPERIMENT 193.**—To measure the pressure exerted by the atmosphere.

The glass tube may be of any length greater than 2-ft. 6-in., but a length of about 2-ft. 9-in. is most convenient. One end should be closed and the bore should be perfectly clean. Pour mercury into the tube until it is full and by tapping dislodge any air-bubbles. Fill the dish with mercury and invert the tube so that its open end is just below the mercury level.

The column of mercury in the tube falls through a few inches and then stops, the space above being known as the "Torricellian vacuum." Actually, as we saw from Experiment 169, it contains a very small quantity of mercury vapour but this is so minute as to be negligible. If we now measure the *vertical* height of the mercury column we find it to be something just below 2-ft. 6-in. or 30-in. (760 mm.). Under certain standard conditions as to altitude, temperature and humidity it would be exactly 760 mm.

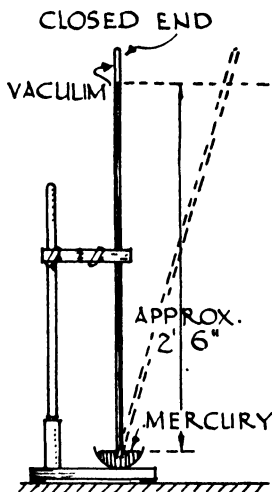


FIG. 371.—Measurement of Atmospheric Pressure.

In this experiment the column of mercury is held in equilibrium by the pressure of the atmosphere on the surface of the mercury in the dish, the pressure on the upper surface of the column exerted by mercury vapour being negligible. The pressure of the atmosphere and that of the mercury at the base of the mercury column are therefore equal and as we know the density of mercury we can calculate the pressure as follows :—

$$\begin{aligned}
 \text{Pressure due to water per ft. head} &= \cdot 434\text{-lb. per sq. in.} \\
 \text{Specific gravity of mercury} &= 13\cdot 6 \\
 \text{Pressure due to 2\cdot 5-ft. head of mercury} &= \cdot 434 \times 13\cdot 6 \times 2\cdot 5 \\
 &= \underline{14\cdot 75\text{-lb. per sq. in.}}
 \end{aligned}$$

This is the normal pressure of the atmosphere and in meteorological work is taken as the unit of atmospheric pressure, called 1 *atmosphere*.

If, in Experiment 193, we had used water instead of mercury the height of water column (again ignoring vapour pressure) would have been  $2\cdot 5 \times 13\cdot 6 = 34\text{-ft.}$

**THE BAROMETER.**—The apparatus used in Experiment 193 constitutes in a simple form the mercury barometer, used to indicate variations in atmospheric pressure, and as this has a bearing upon the general weather conditions the “rise” or “fall” of the barometer is utilized in popular forms of the instrument to indicate probable weather changes. Such instruments are usually of the more convenient “siphon” form shown in Fig. 372, this type being less likely to have its mercury spilt by mishandling. In the second type shown at B the pointer is rotated by means of a small plunger floating on the mercury, hence the advisability of tapping the side of the instrument before observing the reading (in case the plunger should be jammed). These types of instrument are far from accurate owing to the fact that as the top of the column falls the level in the short arm rises, and the true height of the column is the difference between these two levels. This fact is however taken into account in the standard type of barometer used for scientific purposes, adjustment being provided for the purpose, and also a vernier scale for more accurate readings.

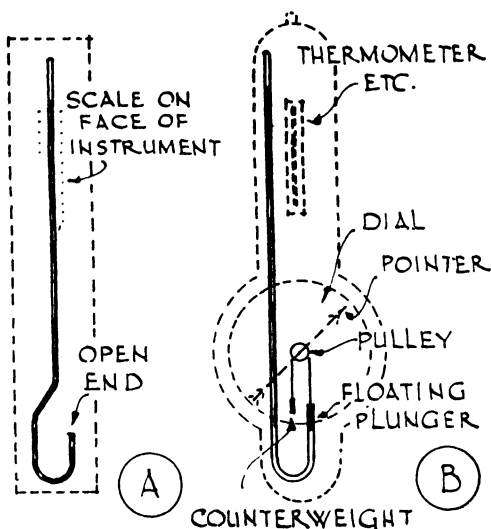


FIG. 372.—The Mercury Barometer.

As water vapour is not so dense as air the barometer reading will be lower in wet weather, other things equal. Altitude also affects the reading since the higher we ascend the less “head” of atmosphere there is—at 900-ft. the mercury level is about an inch lower than at sea level, but the fall in level is not in direct proportion to altitude because the atmosphere is not uniformly dense.

By making suitable corrections for humidity and temperature the barometer may thus be used as an altimeter, to measure heights above sea level. Then, however, the Aneroid barometer is a more suitable type. This, briefly, is a metal box exhausted of air and sealed. The lid of the box then acts as an elastic diaphragm and is depressed according to the intensity of the atmospheric pressure acting on it, this movement actuating delicate mechanism so as to give readings on a dial.

**Utilization of Atmospheric Pressure.**—The pressure of the atmosphere is utilized in many ways, notably in the raising of water and the



manipulation of water supply in various kinds of apparatus. It also gives us a method of determining the specific gravity of any liquid which mixes with water and for which the method of Experiment 188 is thus unsuitable.

**EXPERIMENT 194.**—To determine the S.G. of alcohol by the inverted U-tube method.

The apparatus is shown in Fig. 373. The long glass tubes, both of equal diameter, are suitably supported and together with the T piece, etc. form a kind of inverted U-tube. The lower ends of the tubes are immersed well below the surfaces of water and alcohol respectively contained in beakers.

Suction is applied to the rubber tube until both liquids have risen well up the glass tubes, when the pinch-cock is applied.

What has occurred is that some of the contained air has been removed from the tubes, so reducing the pressure of the remainder which is acting on the surfaces of the liquids inside the tubes. The pressure on the free surfaces of the liquids in the beakers remains at normal atmospheric pressure. To maintain equilibrium therefore the liquids are forced up the glass tubes, but to different heights depending upon their respective densities, since the reduced pressure is the same in both cases.

It follows, then, that a liquid denser than water will not rise so far as the water, whilst a liquid less dense than water will rise to a greater height. By measuring carefully the heights of the columns we can thus compare the two densities. Experimental figures were :—

<i>Ht. of Water</i> (H)	<i>Ht. of Alcohol</i> (h)	<i>S.G. of Alcohol</i> (H/h)
11·2-in.	14·1-in.	·794
19·6-in.	24·8-in.	·79
26·2-in.	33·2-in.	·79

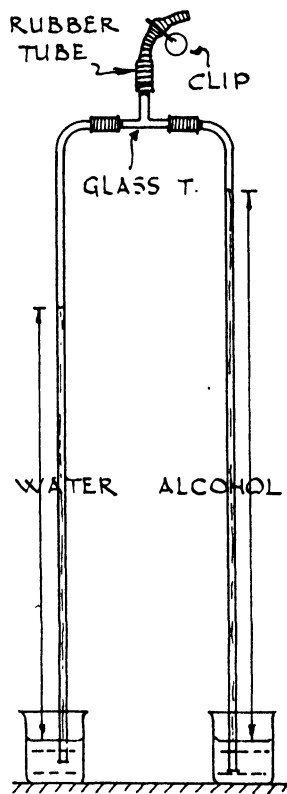


FIG. 373.—S.G. of Miscible Liquid by U-Tube.

**SUCTION PUMPS.**—In the commonest types of pump used for raising water, atmospheric pressure is utilized to do the whole or part of the lifting, according to the distance through which the water is to be raised.

The *lift pump* occurs in many forms but the principle of its action is the same in all cases. The old-time jack pump is perhaps the simplest for purpose of explanation, and is shown in Fig. 374. It consists of a cast iron barrel with a base bolted on, and a leather tail valve between the two. The piston or bucket is a tight sliding fit in the bore of the barrel and is connected by a rod to the upper end of the handle. Through the centre of the bucket is a hole on to which seats the bucket valve, this not being hinged but working up and down vertically by reason of the heavy metal jumper. Into the base of the barrel is screwed the iron suction pipe or a connection for a lead pipe. This reaches down into the water and is usually fitted with a perforated or wire strainer at its foot. As a refinement a foot valve is provided at this point.

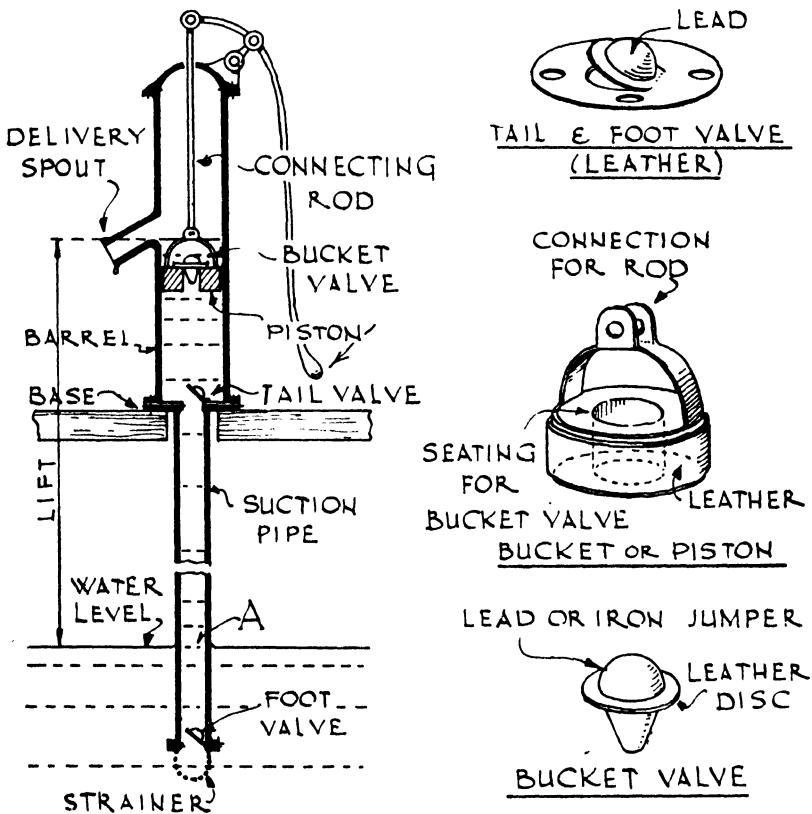


FIG. 374.—The Common Lift Pump.

Now to describe the action of the pump. First it will be seen that all the valves permit water to pass in the upward direction only. Whenever there is a tendency for the water to fall back the valves become closed, as they also do by their own weight when the water is stationary or when

there is no water in the pump. Let us assume that the pump is empty of water—the water level in the suction pipe then coincides with that in the well, because both are acted upon by the pressure of the atmosphere. Now let us operate the pump handle ; at the first *downward* stroke of the bucket the air in the barrel below it tends to become compressed, forcing the tail valve on to its seating but lifting the bucket valve to escape upwards ; at the first *upward* stroke of the bucket, air cannot pass back through the bucket valve and so the air from A up to the bucket, being increased in volume, is reduced in pressure. As a result the water level in the suction pipe rises until the volume of air above A has been reduced to what it was before (in other words until the two pressures are again equal). At each subsequent downward and upward stroke the water in the suction pipe rises by a further step until it passes the tail valve and enters the barrel. A further downward stroke results in the bucket valve admitting the water, whilst at the next upward stroke this water is raised (the bucket valve now being closed) and allowed to overflow at the spout.

The foot and tail valves are not both essential, in fact the foot valve is often dispensed with. Its function is to prevent “ slip,” this being the tendency of the tall column of water in the suction pipe to fall back on each downward stroke of the bucket owing to the slight time lag in the closing of the tail valve. Without a foot valve to check this the action of the pump is liable to be jerky.

The vertical height from the water level up to the bucket valve at the top of its stroke is called the *lift*, and theoretically its maximum is about 34 feet (varying, as has been seen, with altitude, temperature and humidity). This maximum lift is, however, not attainable owing to the difficulty of obtaining perfectly airtight joints, etc., and 25 feet is reckoned as the practical maximum. The suction pipe need not be vertical—so long as the lift is not too near to the maximum the pipe may run in a horizontal direction for a considerable distance, but should have a continuous fall towards the well.

It should be realized that the pump does not actually lift the water (except after it has passed the bucket valve)—it merely enables the water to be forced up the suction pipe by atmospheric pressure acting on the surface of the water in the well, this being greater in intensity than the air pressure within the pump barrel.

The *lift and force pump* is a variation of the lift pump, used to raise the water and to deliver it to a point higher than the pump—in practice not more than about 10 feet higher. It differs from the lift pump in that the delivery spout is turned upwards and continued as a delivery pipe, with a valve at its foot to support the water column on the downward stroke of the bucket. The top of the barrel must also be closed and a

watertight joint made by packing the connecting rod. This type of pump is illustrated in Fig. 375, which shows an air chamber fitted to the rising delivery pipe. The function of the air chamber is to smooth out the flow of water up the pipe and so to make pumping easier. Without it the inertia of the whole column of water must be overcome at each upward stroke of the bucket, but when it is fitted the entrapped air in the chamber is compressed at the upward stroke and its pressure released at the downward stroke, so maintaining a continuous flow. For fitting to a horizontal pipe the air chamber usually takes the form shown in Fig. 376.

The *force pump* is used for raising water and forcing it to heights greater than can be done by a lift and force pump. The intensity of pressure on the working parts of such a pump increases with the "throw," *i.e.* the height to which the water is forced; this is the reason why the lift and force pump has a limited throw, the pump not being specially constructed to withstand such pressures. The force pump, on the other hand, is of more robust construction, and a simple type is shown in Fig. 377. The delivery pipe is taken from the barrel near the base of the pump, and a solid piston used in place of the bucket and valve. Water is forced up the delivery pipe on the *downward* stroke of the piston. This type of pump is also used in hydraulic machines for building up pressures.

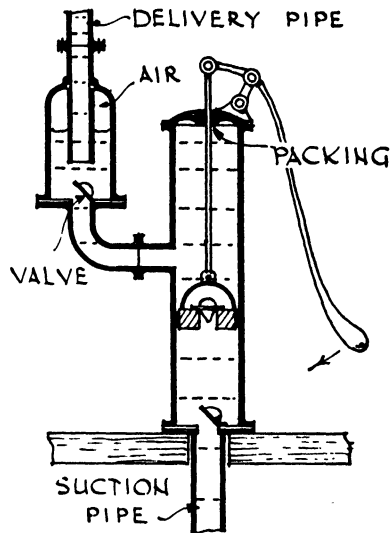


FIG. 375.—The Lift and Force Pump.

The pumps already mentioned all belong to what might be termed the "cylinder and piston" type, and it is clear that if used for water that is not clean, such as that from sumps, excavations, etc., excessive wear would result and their working life would be very brief. Partly for this reason pumps have been devised which utilize other methods of procuring the reduced pressure necessary to secure the lift by atmospheric pressure. The more common of these may be briefly described.

The *diaphragm pump* works upon exactly the same principle but has a circular flexible diaphragm of leather or rubber composition in place of the piston. The up and down movement is more restricted (see Fig. 378) but this is made up for by the much greater diameter, which may be from 6-in. to more than 12-in. The diaphragm is fixed all around

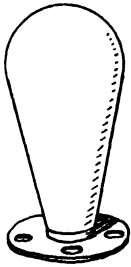


FIG. 376.—  
Cast-Iron Air  
Chamber.

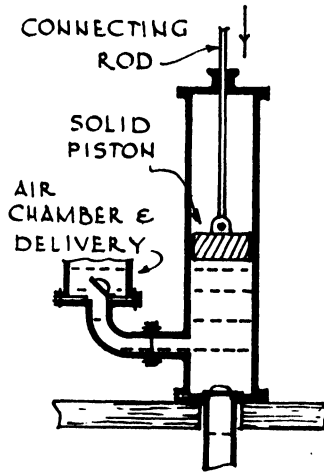


FIG. 377.—The Force Pump

its circumference and the “barrel” may therefore be of any shape—the type shown consists of two hemispherical portions bolted together with the diaphragm in between. It may be used as a lift or a lift and force pump, according to whether a spout or a delivery pipe is fitted.

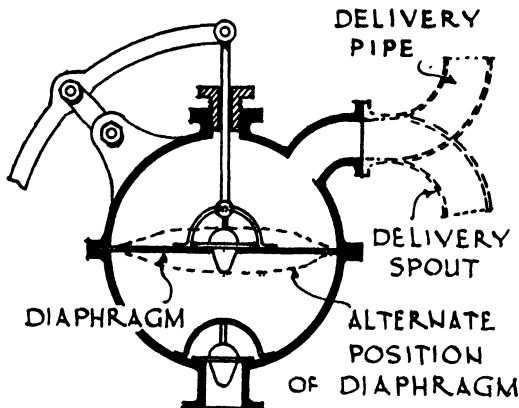


FIG. 378.—The Diaphragm Pump.

In a slightly different form it is known as the Contractor’s Pump, used for quickly clearing trenches and other excavations of accumulated water. Here the problem is to raise muddy and gritty water in

quantity from a small depth and to discharge it direct from the pump, by spout into a shute or by large diameter hose. The suction pipe is flexible hose and has a coarse strainer to keep out large stones which would otherwise not be able to pass the valves. It is illustrated in Fig. 379.

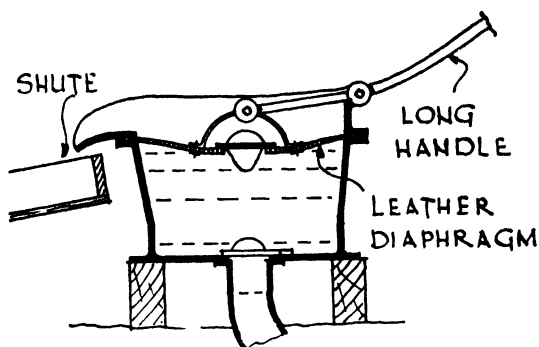


FIG. 379.—The Contractors' Pump.

Another type of pump popular nowadays for ordinary purposes is the *semi-rotary* or *wing pump*. This is illustrated in Fig. 380 which shows the pump in elevation with the flat face plate or cover removed. The wing, through which pass two holes covered by flap valves, is pivoted on the spindle and is made to oscillate by working the handle back and forth. The tail valves, one on either side, cover the two inlets from the suction pipe, and the pump is therefore double-acting, throwing water on both backward and forward strokes. Some pumps of this type have balls in place of the flap valves and are claimed to withstand longer wear on this account, especially with gritty water. The simple and stout construction of these pumps, together with the fact that the spindle packing and face plate washers ensure sound joints, enables them to withstand high pressures and when used as lift and force pumps they will easily force water to a height of 75 feet.

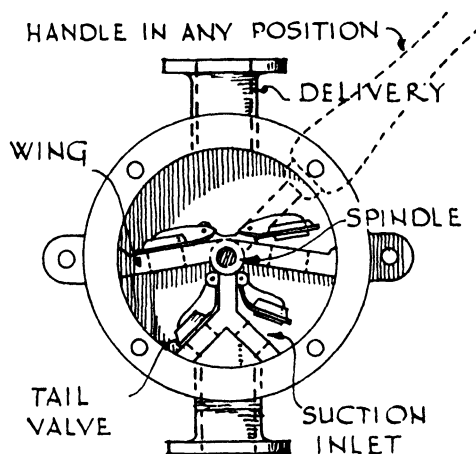


FIG. 380.—The Wing or Semi-Rotary Pump.

To raise water from a depth of more than 25 feet the barrel and piston type of pump may be located down the well or borehole (within 25 feet of the water) and a long connecting rod fitted to reach the handle or other power at the surface. Even so the range is severely limited, and in cases where the water is at great depth power-

driven *air-lift pumps* are necessary. These work on the principle of increasing the lift by increasing the air pressure on the surface of the water, and by aerating the water to reduce its density. To accomplish this highly compressed air is admitted to the borehole, which is sealed, and by a long tube to the water at the foot of the suction pipe.

**THE SMOKE TEST FOR DRAINS.**—This is really an air pressure test, the smoke only being used so as to become visible in case of leakage and so to indicate the position of the fault. It is accepted by some authorities as a test for underground drains, with an appropriate maximum pressure, but it is not really suitable because all points of the drain are subjected to equal pressure, whereas the water test for underground drains (page 419) reproduces the actual conditions of accidental stoppage. For waste and soil pipes, on the other hand, the water test is unsuitable because of the excessive pressure produced at the foot. Such vertical pipes seldom become blocked, the test being merely for the soundness of the jointing.

To apply the test the drain is plugged at the nearest inspection chamber and the smoke applied at this point from a smoke machine. If it issues from the open end of the vent pipe and from the traps to the various fittings (these being unsealed) the pipes are known to be clear. The vent pipe outlet and the traps are then plugged, and the pressure built up by means of the pump on the machine, escaping smoke indicating a faulty joint.

In old underground drains faults may be located, if the soil is porous, by plugging and applying smoke under pressure. Any smoke escaping through a broken joint or pipe, rises through the soil and indicates approximately the position of the fault.

**SIPHONAGE.**—If the working of the lift pump is understood the phenomenon of siphonage will present no difficulty. Fig. 381 shows a siphon in its simplest form—just a bent tube AB with one end A immersed in liquid, and the other end B at any level lower than the free surface in the beaker, usually below A. AC and CB are the two arms of the siphon. If the tube were straight, as shown by the dotted lines, and the pressure of air inside it were less than 1 atmosphere the liquid in it would rise under the pressure of the atmosphere on the surface of the liquid in the beaker. If there were a vacuum in the tube the liquid would be forced up to a

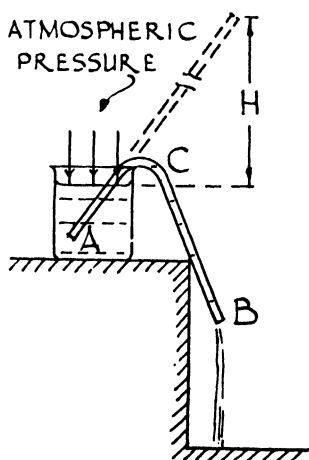


FIG. 381.—Principle of Siphonage.

height  $H$  depending upon the specific gravity of the liquid—34 feet for water. But the tube is bent down from a point  $C$  below this; thus, assuming a vacuum or a pressure appreciably below 1 atmosphere in the tube, the liquid is forced over the bend  $C$  into arm  $CB$  and upon reaching a level below that in the beaker it flows down  $CB$  and out of open end  $B$ , followed by the remainder of the water. Siphonage ceases when the water level in the beaker has fallen to point  $A$  for then air is admitted through the open end of the tube or, as in the case illustrated in Fig. 382, when the levels in the two vessels coincide.

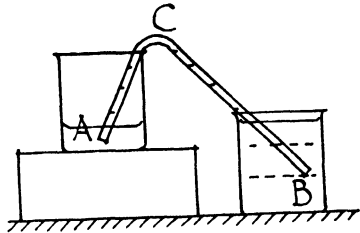


FIG. 382.—Simple Form of Siphon.

Referring to Fig. 382 it is seen that the liquid in the two beakers and the siphon is a single body of liquid with a common free surface. If therefore we were to remove the lower beaker so as to expose the open end  $B$  we should expect the liquid to flow out via this, the lowest point. This it does just as surely as if we had knocked a hole in the base of the upper beaker.

In practice, to start the siphonic action, either air can be exhausted from the first arm of the siphon by suction, or the whole tube can be filled with liquid before inverting and placing in position.

EXPERIMENT 195.—To produce siphonic action.

A piece of glass tubing should first be bent so as to enable the phenomena discussed above to be verified. (Figs. 381 and 382).

Then repeat, but using a long piece of rubber tubing so that point  $C$  can be several feet above  $A$ .

Next fit up the siphon shown in Fig. 383 and, whilst it is in action, open the clip so as to admit air. The water in both arms will fall back into the respective beakers. Re-start the action by suction through the rubber tube, closing the clip as soon as siphonage begins.

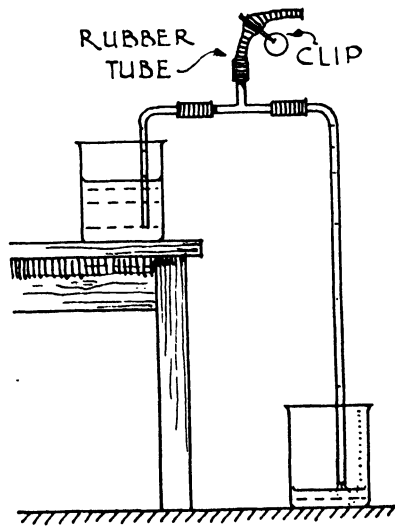


FIG. 383.—Experiment on Siphonage.



## APPLIANCES UTILIZING SIPHONIC ACTION.

## EXPERIMENT 196.—An experimental W.C. FLUSHING CISTERN.

The apparatus depicted in Fig. 384 comprises a retort stand, an inverted wide-mouthed bell jar and a tank. Through the bung (preferably pushed in from above) passes a straight glass tube projecting upwards just sufficiently to fit an inverted test tube as shown. This test tube is of soft glass and is flared out at the mouth by heating strongly in a Bunsen and then widening and "crinkling" with a piece of metal or glass rod.

Admit water until the level is almost up to the top of the glass tube and then cut off the supply. Now with finger and thumb raise the test tube a few inches and let it drop. The water level in the tube is momentarily raised and as the water overflows into the vertical tube siphonic action commences and continues until air is admitted at the mouth of the test tube. The two arms of the siphon are the vertical glass tube B and the annular space between this and the test tube A.

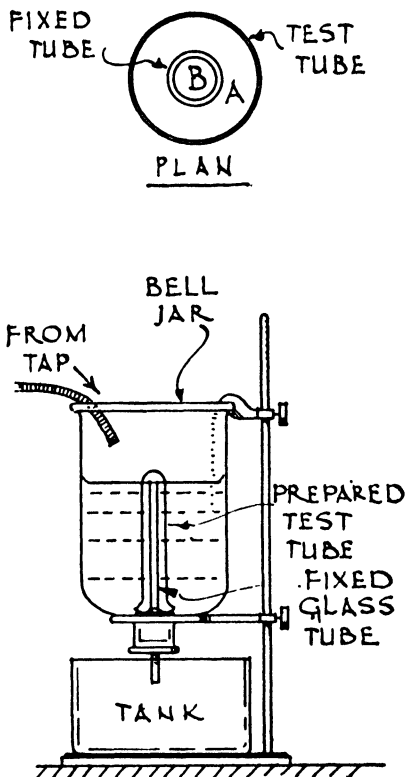


FIG. 384.—Experimental Siphonic Flushing Cistern.

The practical form of W.C. flushing cistern is of cast iron or enamelled steel, the test tube being replaced by a heavy cast iron "bell" and the vertical glass tube by a "stand pipe," a continuation of the flush pipe. This is of appreciable diameter so as to empty the cistern rapidly and produce as forcible a flush as possible. Early types of flushing cistern had a plain outlet covered by a heavy plug which was raised, and the flush operated, on pulling a chain. This, however, permitted water to run to waste into the W.C. pan in the event of the plug and its seating, or the ball tap, being faulty, and because of this these cisterns were banned by water authorities. With the best siphonic cisterns the water cannot

run to waste down the flush pipe but instead runs out via an overflow pipe (the "warning" pipe) to a point where it can be seen, and the matter put right, without delay. For this reason siphonic cisterns, when first introduced, went under the name of "water waste preventors." The

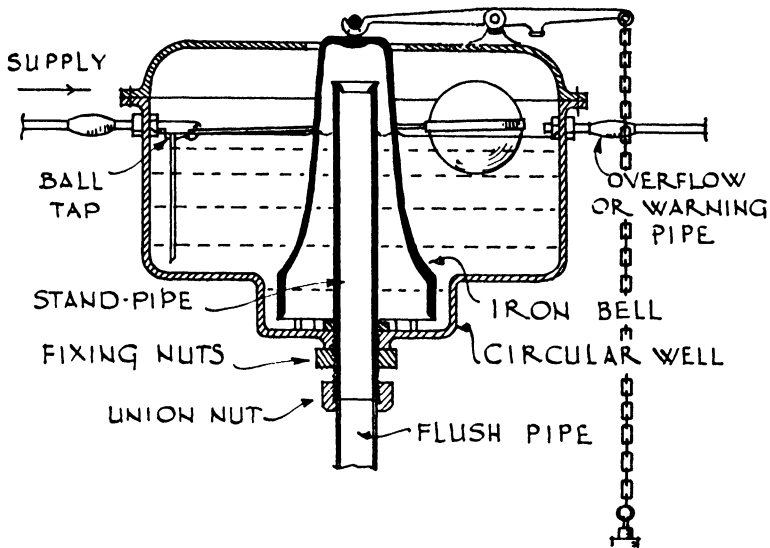


FIG. 385.—W.C. Flushing Cistern—Bell Type.

Bell or "Pull and Let Go" type, shown in Fig. 385, is the simplest and best; others, usually more expensive, have the siphon in the form of a bent copper or brass tube, the siphonic action being started by forcing water over the bend by some arrangement of cylinder and plunger operated by a lever or push button. A typical one is given in Fig. 386. Most water authorities permit a maximum flush of two gallons and this is only sufficient

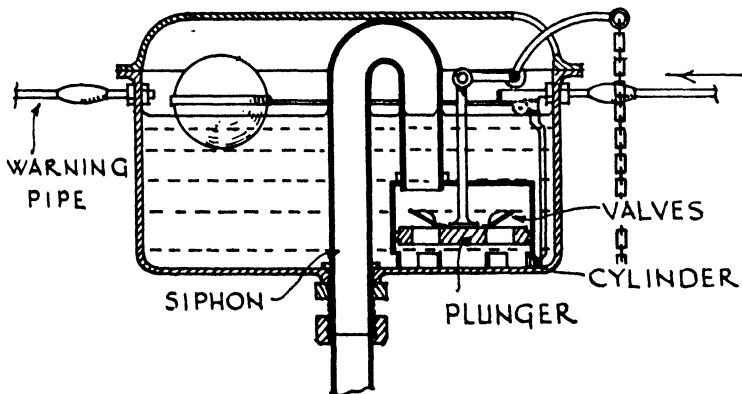


FIG. 386.—W.C. Flushing Cistern—Plunger Type.

if the pan is of particularly satisfactory design. To make the most of this limited quantity of water most cisterns have a circular well such as shown in Fig. 385, the small depth of water left after the flush then being of smaller volume than if it were spread over the whole area of the cistern.

**EXPERIMENT 197.**—An experimental AUTOMATIC FLUSHING CISTERN.

The apparatus used in experiment 196 may be used, or the siphon may be in the form of a bent tube as in Fig. 387. As the water level rises in the bell jar it also rises up the first arm of the siphon and, upon passing the bend, commences the siphonage. After the bell jar has emptied and siphonage has ceased by the admission of air bubbles it fills up again, the water supply being continuous.

In practice the automatic flushing cistern is used for flushing urinals, etc., automatically at pre-determined intervals, this being governed by the rate at which the water is allowed to enter. A much larger edition is used for flushing drains that are not altogether self-cleansing by reason of insufficient fall being obtainable. In this case the tank is of concrete or rendered brickwork sunk into the ground and covered by a cast iron frame and lid. Fig. 388 illustrates the kind used for flushing sanitary fittings and this should be compared with Fig. 385. To ensure siphonage in the latter appliance the entire cross-section of the standpipe must be

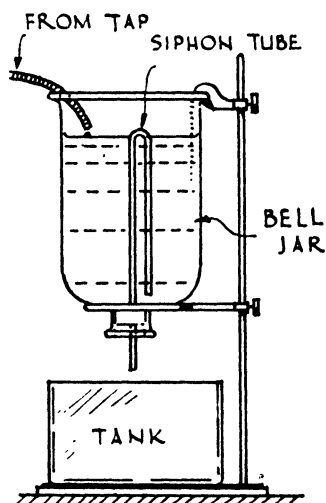


FIG. 387.—Experimental Automatic Flushing Cistern.

filled with water and the violent movement of the bell usually ensures this, but various aids to this end are in use. One is shown in Fig. 385, viz. the lip at the mouth of the standpipe, whilst another is indicated in Fig. 388, viz. the bulge in the standpipe; both of these expedients ensure this end by deflecting the water stream inwards across the bore of the pipe. In the automatic cistern, however, the dome is fixed and the water level rises very gradually. There is thus only a mere trickle over the lip of the standpipe and even the expedients mentioned are incapable of starting siphonage. (In Experiment 197 the standpipe is extremely narrow and this is why the apparatus "works.") To assist in this is the function of the water seal at its foot, and it does so in this way:—As the water rises in the dome the air above it, and that in the standpipe, is subjected to compression and some of it is forced out at the bottom where the water

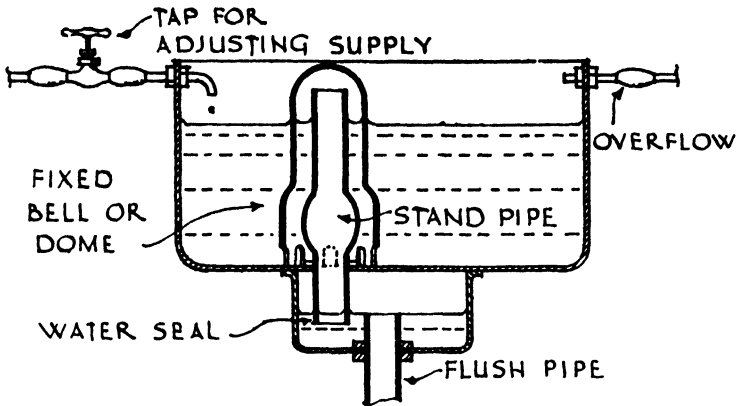


FIG. 388.—Automatic Flushing Cistern.

seal prevents its return. Upon the water passing over the top of the pipe it takes further air with it, so reducing the pressure in the dome to less than 1 atmosphere and this enables siphonage to start.

The usual *W.C. pan* is of the "wash-down" type shown in Fig. 389 in which the flush circulates around the flushing rim, so cleansing the whole inside surface of the pan, and cascading on to the contents forces them through the trap by pressure. But if a pail of water be emptied forcibly into the pan directly over the outlet the contents of the pan are emptied much more quickly, because the action now is partly by siphonage, the sudden large volume of water being sufficient to fill the entire cross-section of the branch soil pipe (or of the drain itself if the *W.C.* is situated on the ground floor—this is the case illustrated). To do this satisfactorily requires at least 2 gallons of water, leaving no surplus from a total flush of this quantity to pass around the flushing rim and so re-seal the trap after discharge.

Where a larger flush is possible, say  $2\frac{1}{2}$  gallons, a *siphonic W.C.* can be used, and is much more effective. Fig. 390 shows the "single trap" type which reproduces the conditions mentioned in—

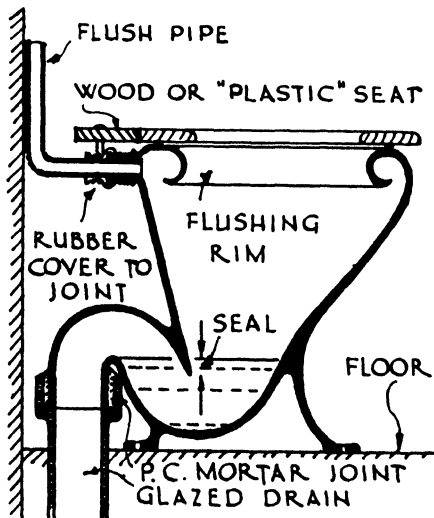


FIG. 389.—"Wash-Down" *W.C.* with S-Trap Outlet.

connection with the pail of water but also retains a small proportion of the flush for cleansing the surface and re-filling the trap. For greater effect the water seal is much deeper than in the "wash-down." In Fig. 391 is shown the "double trap" type, more effective still, in which the main flush does not enter the pan at all but is directed into the second trap so "drawing out" the contents of the pan by siphonage, with startling rapidity.

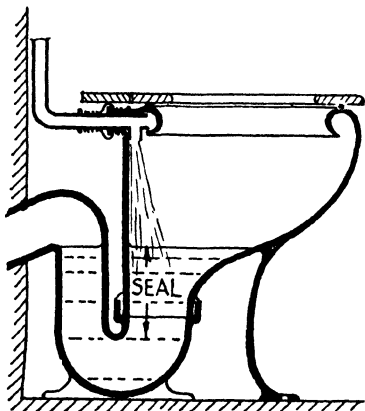


FIG. 390.—Siphonic W.C.—  
Single Trap Type.

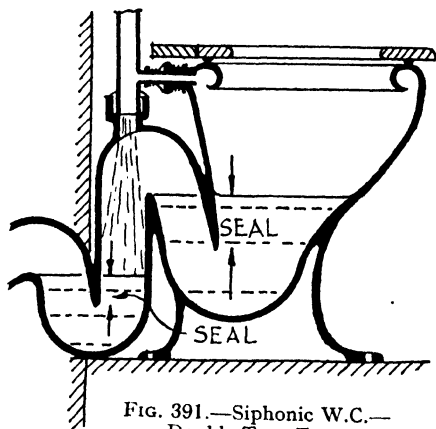


FIG. 391.—Siphonic W.C.—  
Double Trap Type.

### ANTI-SIPHONAGE PIPES.

EXPERIMENT 198.—To illustrate "anti-siphonage."

Fit up the apparatus illustrated in Fig. 392, suitably supported in a retort stand. Fill the trap with water, see that the clip is tightly closed (this is equivalent to dispensing with tube A) and run water through the vertical tube C. This stream of water passes the open end of tube B and in doing so draws some of the air from B, carrying it away in the form of bubbles. The air pressure acting on the surface of the water at D is now less than the atmospheric pressure acting at E, with the inevitable result that E becomes depressed, so forcing some of the water at D over the trap into tube B and so to waste. At the cessation of the flow down tube C the original atmospheric pressure on D is restored (via tubes C and B) and the two levels again coincide but on a lower plane. If the flow of water has been at considerable velocity the whole of the water may have been removed from the trap.

Now fill up the trap again and repeat the experiment *having first removed the clip from tube A*. This time the water levels remain undisturbed no matter how fast the flow of water down tube C. This is because, although air is being removed from tube B as before, it is being replaced by air drawn in through A so as to maintain the atmospheric pressure on D.

In Experiment 198 the glass trap represents the trap of a sanitary fitting such as a sink or bath, the tube B is the branch waste pipe and the tube C the main waste pipe discharging at the foot into a gully connected to the drain. If the fitting is a W.C., slop sink or urinal the tube B would be the branch soil pipe and C the main soil pipe connected at the foot direct to the drain. In either case tube A, with the clip removed, is an "anti-siphonage" pipe (otherwise "waste-ventilating" or "soil-ventilating" pipe). It is a necessary adjunct to each of a range of fittings, connected to a common waste or soil pipe, except the highest one which is

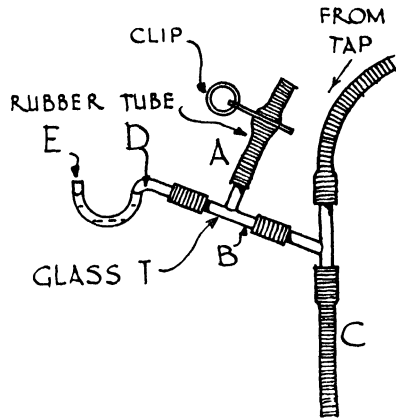


FIG. 392.—Experimental Anti-Siphonage Pipe.

unaffected by other discharges into the main pipe. Fig. 393 shows diagrammatically a number of such fittings on different floors and with a single soil pipe carried up above the roof as a ventilating pipe. The ground storey and first storey traps could become unsealed by the discharge of higher fittings and thus require anti-siphonage pipes. These are taken from the top of the trap in each case and connected to a main anti-siphonage pipe which must be carried up to a height at which the discharge of sewer gas can cause no nuisance. In practice, to save unnecessary piping and to prevent further unsightliness, its upper end is connected to the ventilating pipe (the upward continuation of the main soil pipe) at a point well above the level of the highest trap.

It should be realized that the "highest" fitting means the fitting furthest from the drain—not necessarily at the greatest height above ground. A range of fittings alongside each other on the same storey requires similar precaution against siphonage of the traps.

It will be clear that the provision of anti-siphonage pipes greatly complicates the plumbing besides increasing the cost, especially where there are many fittings grouped together as in commercial, industrial and public buildings. It is perhaps not surprising then that alternative methods, acceptable to sanitary authorities, of dealing with wastes are often sought. In the case of a range of lavatory basins or urinals the wastes of each fitting may not require to be trapped provided that they discharge into an accessible common pipe or channel which is itself trapped before being taken to the main soil or waste. As an alternative, for sinks or basins, special traps are available which do not readily become unsealed. Some of these provide merely an extra-deep seal,

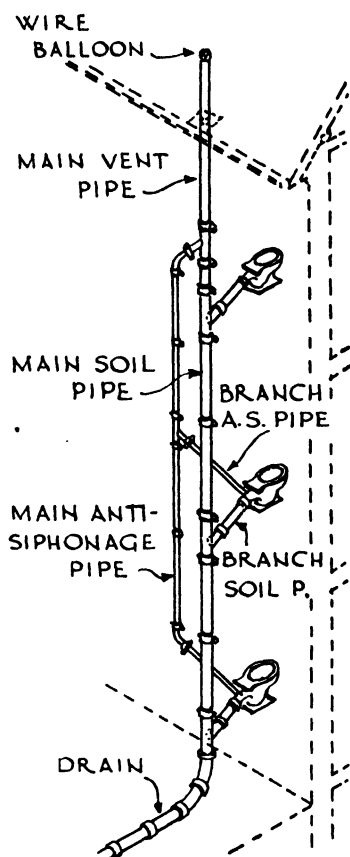


FIG. 393.—Anti-Siphonage Pipe System to Range of Fittings

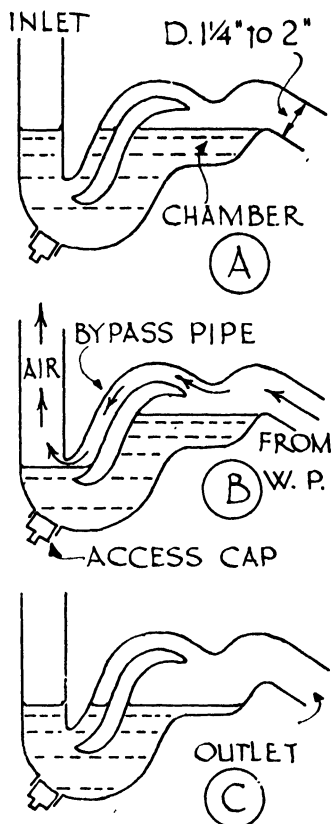


FIG. 394.—The Greenwood "Anti-Vac" Trap.

but at least one type—the "Anti-vac"—incorporates a chamber containing extra water which automatically "tops up" the trap after it has become affected. It is shown in section in Fig. 394 where at A it is full, as normally; at B water has been withdrawn by siphonage until the first seal is broken; siphonage has now ceased and at C is the seal restored. Continued and persistent siphonage would, of course, reduce the amount of water further still but, as each discharge of the fitting replenishes the trap as at A, with normal use there is little fear of its remaining unsealed for long.

#### BALL TAPS

Although perhaps outside the strict scope of the present chapter attention might best be directed at this stage, whilst dealing with water appliances, to the method of controlling their supply of water. The

ball tap is a means of regulating the ingress of water to a vessel utilizing the buoyancy of a floating ball or cup to operate the tap. Fig. 395 illustrates in diagrammatic form the principle upon which the buoyancy of the water acting on the ball, with a large leverage, is arranged to give a greater force acting to close the orifice of the tap, by reason of its smaller leverage. In all the types of tap illustrated it will be seen that when the vessel is empty the weight of the ball causes the tap to be fully open, so admitting water at its maximum rate of entry. As the water level rises the ball floats upwards, the washer simultaneously approaching its seating and reducing the rate until when the water has reached its predetermined level the washer is held firmly against its seating, so completely cutting off the supply.

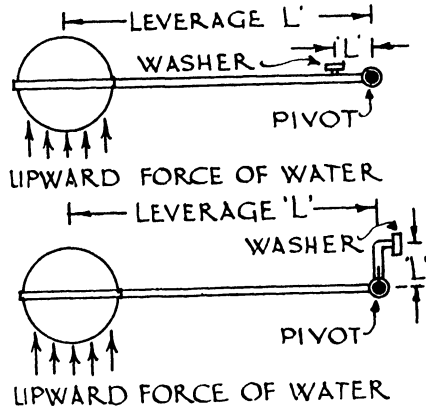
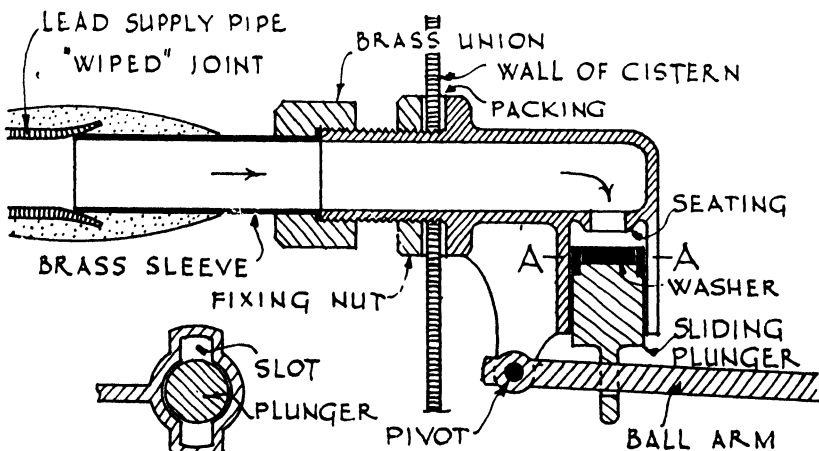


FIG. 395.—Principle of the Ball Supply Tap.

Figs. 396 and 397 illustrate respectively the "Croydon" and "Portsmouth" taps, both types in which the full pressure of the water supply is resisted by the ball at the end of its arm. These are suitable for the low pressures involved in cases where the vessel is supplied from a storage cistern; such are the majority of W.C. flushing cisterns and



PLAN A-A Showing slots for egress of water.

FIG. 396.—The "Croydon" Ball Tap.



also storage cisterns in districts where the mains supply is at a low pressure. For high pressures, such as storage cisterns where the mains pressure is high or where flushing cisterns are supplied direct from such mains, the balanced types (Figs. 398 and 399) are better as in these some of the

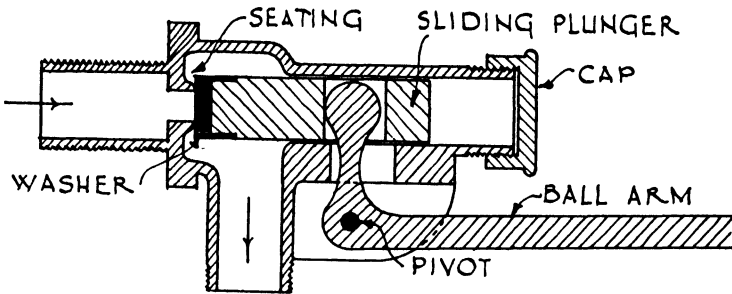


FIG. 397.—The "Portsmouth" Ball Tap.

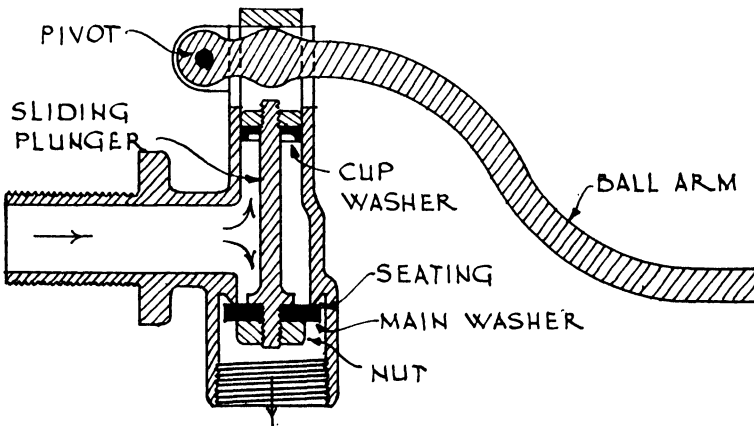


FIG. 398.—"Balanced" Ball Tap—Vertical Type.

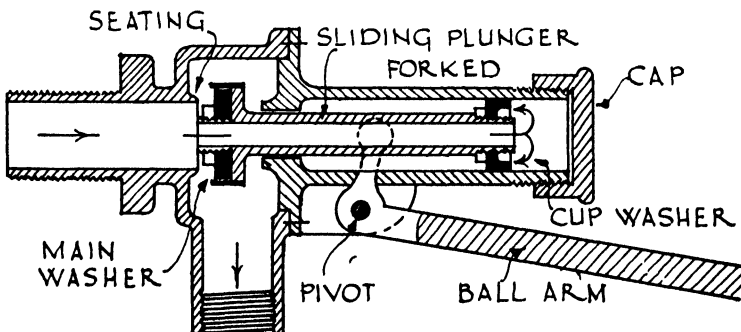


FIG. 399.—"Balanced" Ball Tap—Horizontal Type.

pressure acts in a reverse direction on a cup washer, so lessening the strain on the ball arm.

**THE SPRAY GUN.**—The spray gun is being increasingly used in painting and decorating work, especially for the more modern synthetic and cellulose finishes which depend largely for success upon speed of application. Fig. 400 shows the principle underlying some types of gun, and utilized also in the simpler spray used to "fix" crayon and charcoal drawings which would otherwise smear. The jet of air under pressure is directed across the top of the vertical tube the lower end of which dips into the liquid in the container. This reduces the air pressure in the tube, causing the liquid to rise, to be "atomized" upon reaching the top.

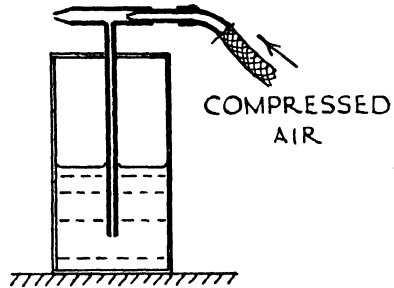


FIG. 400.—Principle of the Spray Gun.

#### 4. MISCELLANEOUS FLUID PRESSURE PROBLEMS.

The pressure exerted by air in motion is of great importance in the design of certain types of structure, the stresses produced by wind pressure being in some cases much greater than those resulting from normal dead and superimposed loads. The wind acts as a fluid and exerts pressure normal to the surface against which it acts. This pressure is not uniform and also varies at different heights and is affected by adjacent obstructions. In addition the air pressure on the leeward side of a structure is rarified, this resulting in suction which increases the stresses, being equivalent to a higher actual pressure. The wind pressures to be allowed for in design are laid down in various regulations. A wind of 100 miles per hour is by no means unknown in some parts of this country and this is equivalent to a pressure of 30-lb. per square foot of surface. Add to this any suction effect, and also impact effect if the wind is in gusts, and it will be appreciated that wind must be seriously reckoned with in any tall and slender structure in an exposed situation.

Another case in which fluid pressure must be considered is the design of retaining walls. The overturning pressure on a wall retaining water is much greater than on one retaining earth, but the latter may easily become overloaded in the event of the earth behind it becoming waterlogged. It is to prevent this that weep-holes are constructed along the base of such a wall.

In the design of timber shuttering to receive concrete it must be remembered that for a certain time the concrete is in a wet state and so exerts considerably greater pressure than consideration of the known density of finished concrete might lead one to suppose. Especially is this so in the case of formwork for high walls or columns, where lateral pressure near the base is often sufficient to require special precautions.

"Granular" solids such as grain, cement, small coal, etc., when confined act as fluids, and the design of containers or other storage arrangements for them is highly specialized on account of this.

All these problems will be further discussed in the succeeding volume.

### Exercises.

1. Two cold water taps are fixed 4-ft. vertically above the ground floor of a house, one served direct from the rising main and the other from the storage cistern. The public water main is 5-ft. 6-in. vertically below the ground floor (the water being at a pressure of 40-lb. per sq. in.) and the cistern is fixed 13-ft. above the ground floor and contains 2-ft. of water. What is the pressure on both taps?  
(Ans. 37·61-lb. per sq. in. and 4·77-lb. per sq. in.)
2. In a specific gravity U tube the heights of the two columns of liquid were :—  
Water 22·6-in., specimen liquid 24-in. What is the S.G. of the liquid?  
(Ans. ·94)
3. What is the gas pressure in lb. per sq. in. when a U gauge gives a reading of 2½-in. of water column?  
(Ans. ·081-lb. per sq. in.)
4. A tank 10-ft. × 5-ft. × 4-ft. deep is full to within 6-in. of the top with boiled linseed oil (S.G. ·94). The outlet, 3-in. in diameter, is 4½-in. from the bottom and is sealed by a plug. What is the amount of the force acting on the end of the plug and tending to push it out?  
(Ans. 8·64-lb.)
5. A hydraulic testing machine has a ram 10-in. in diameter and the diameter of the hand-pump plunger is 1-in. What force is exerted by the ram for each 10-lb. stroke of the pump?  
(Ans. 1,000-lb.)
6. A wash-down W.C. pan has a water seal of 1½-in. What reduction of pressure in the branch soil pipe would be just sufficient to unseal the trap?  
(Ans. ·063-lb. per sq. in.)

## ELECTRICITY

1. *Electric Current.*
2. *Effects of Electric Current.*
3. *Electro-Magnetic Induction.*
4. *Measuring Instruments.*
5. *Electrical Power and Energy.*

## 1. ELECTRIC CURRENT.

Reference has been made in Chapter I to the Atomic Theory of Matter. From this we are led to conclude that the atom consists of a nucleus around which rotate one or more *electrons*. These are many times lighter than the nucleus and are of an opposite nature to it—for convenience they are classed as negative and positive respectively. If we imagine a single drop of liquid magnified to the size of the earth, and its atoms increased in size in proportion, the complete atom would be about 3 feet across, but the “diameter” of the nucleus would be only about  $\frac{1}{2500}$ -in. and the equally small electrons would be spinning around it at great speed *in empty space*.

**Nature of Electricity.**—All atoms are normally electrically neutral, *i.e.* neither positive nor negative, and the negative “charge” of the electrons then cancels out the positive charge of the nucleus. The hydrogen atom is the simplest, consisting of a single electron travelling around a simple nucleus or *proton*. The atom of helium has two rotating or “free” electrons (negative) and a nucleus comprising four protons (positive) and two “fixed” electrons (negative), the complete atom being thus neutral as before. In any atom the number of free electrons corresponds to the atomic weight of the substance; for the higher values of atomic weight therefore the atom must become more complicated in structure.

In an atom which has a number of free electrons these do not necessarily travel in the same orbit; some may be nearer to the nucleus than others (as with the planets and the sun) and possibly not rotating in the same plane, nor even in the same direction. The further from the nucleus the orbit the less strongly are those electrons held, and in certain circumstances these loosely-held ones may leave one atom and join another. When this occurs the original atom is deficient in negative electricity, whilst the other atom, which now has more electrons than its normal complement, has an excess of negative charge.

**ELECTRIC POTENTIAL.**—In Chapter XVIII we have discussed the question of potential energy. If we consider two tall vessels connected near the bottom by a horizontal pipe with a tap, and containing water to different levels, each column of water has a certain potential energy. The difference in the amounts of their potential energy when the tap is closed is cancelled by opening the tap and permitting the water in both vessels to assume the same level. This it does by reason of the difference in water pressure at the ends of the pipe.

When the atoms in one part of a body, say a length of wire, are for some reason deficient in negative charge some of the free electrons from adjacent atoms may forsake their own nuclei and join the others. Further transfer of free electrons may have to take place in other parts of the wire in order to bring the whole into a state of electrical equilibrium. This "drift" of the free electrons is called a *current* of electricity, and the number of electrons affected is enormously great, even for an extremely small current.

The reason for this "flow" of electricity is a difference, in different parts of the body, of electrical "pressure" (compare with the difference of water pressure) or *potential*, called the *potential difference*—abbreviation P.D. That part of the body which has a positive charge (deficient in free electrons) is a region of high potential and the part which is charged negatively (excess of free electrons) is at low potential. The current is therefore a flow of electricity (negative) from a region of low potential to a region of high potential. In spite of this conclusion, as early electrical theories assumed that the flow was of *positive* electricity in the reverse direction, the idea is universally retained as a convention, *i.e.* that electricity is positive and flows from high to low potential regions.

To return to the water analogy, suppose the two vessels to be of different diameters (Fig. 401) and that although they contain identical quantities of water the level in the smaller vessel is higher than that in the larger one. It is a difference in level, not in quantity, which produces the difference in water pressure at the ends of the horizontal pipe, resulting in the flow of water. Alternatively we may think of a small hot body losing heat to a larger cool body, although both may contain identical quantities of heat. Similarly if we have two bodies, a small one and a larger one, charged with identical amounts of electricity, and we bring them into contact, electricity will flow from the smaller one to the larger one until both are at the same potential.

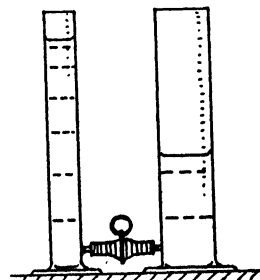


FIG. 401.—Flow of Water due to Difference in Level.

CONDUCTORS AND INSULATORS.—As might be expected, it is found that materials vary in the ease with which they permit a flow of electricity to take place. Some substances, although subjected to a potential difference, do not suffer a measurable flow of current; this is because their atoms have very few free electrons so loosely held as to become easily transferred. Instead such a substance is subjected to a state of electrical *strain*; it is called an *insulator*. Other materials are so constituted as to permit the movement of free electrons with great facility; this type of substance is termed a *conductor*. No material is a perfect insulator, none a perfect conductor, and there is no definite dividing line. It is therefore usual to refer to a material as a good or bad conductor (bad or good insulator respectively). Metals are good conductors, silver being the best followed closely by copper, whilst paraffin wax, mica and rubber are amongst the best insulators (in that order). Fibrous materials like cotton, wood and paper are good insulators but only if kept dry, since any moisture in their pores enables the current to be conducted away.

The ability of a material to conduct electricity is referred to as *conductivity*, and the reverse of this, *i.e.* the ability to impede the flow of current, is called electrical *resistance*. A good conductor therefore has low resistance, whilst good insulators have high resistance.

ELECTRO-MOTIVE FORCE.—This is the term (abbreviated E.M.F.) used to denote the electrical force required to “drive” the current through a conductor against its resistance. It has been shown that a P.D. is necessary before a current will flow; the E.M.F. is the force required (supplied by the source of the current—cell, battery of cells, etc.) to produce this potential difference. Referring again to Fig. 401 the energy used in raising the level of the water in the smaller vessel corresponds roughly to the E.M.F. whilst the head of water available (the difference in levels) corresponds to the potential difference.

A cell or battery of cells has been mentioned as a source of E.M.F. and it is produced in such a case by chemical action. There are other means, notably the generator (including the “mains”) in which it is produced by other means—to be explained in due course.

ELECTRIC CIRCUIT.—As metals are the best conductors they are used, both in experimental and practical work for “carrying” currents, in the form of wire or strip, usually round wire. The use of silver is precluded by the question of cost so that copper is the metal invariably employed, except for instance where a higher mechanical strength is necessary.

The resistance of a wire varies:—Directly as its length (any length of wire may be regarded as a number of equal smaller lengths joined end to end to make an equivalent total length), and inversely as its cross-sectional area (any length of wire is equivalent to several equal lengths of

thinner wire joined throughout their length, and giving a combined equivalent cross-sectional area).

The source of supply of the current terminates in two separate terminals, which are merely arrangements for securing in metallic contact the two ends of the wires forming the *circuit*. An electrical circuit corresponds to a circulation in a hot-water system and must similarly be complete before current will flow. If the hot-water pipes have a fault, water leaks away; similarly the wires forming the electrical circuit must be protected from leakage of current by being "insulated." The pipes must be of sufficient bore and strength to carry the required quantity of water and to resist the water pressure: similarly the wires must be suitable as to cross-sectional area from the standpoint of current-carrying capacity and resistance. Again, just as a stop tap may be inserted in the system of piping to arrest the flow of water at will, so a switch may be arranged in the system of wiring to "break" the circuit. A switch is merely an arrangement to leave a gap in the wiring which may be bridged or left at will.

Fig. 402, A, shows a simple circuit comprising a pocket torch bulb connected by wires to the terminals of a cell or accumulator, and with a switch interposed in one of the wires. At B is shown the conventional diagram.

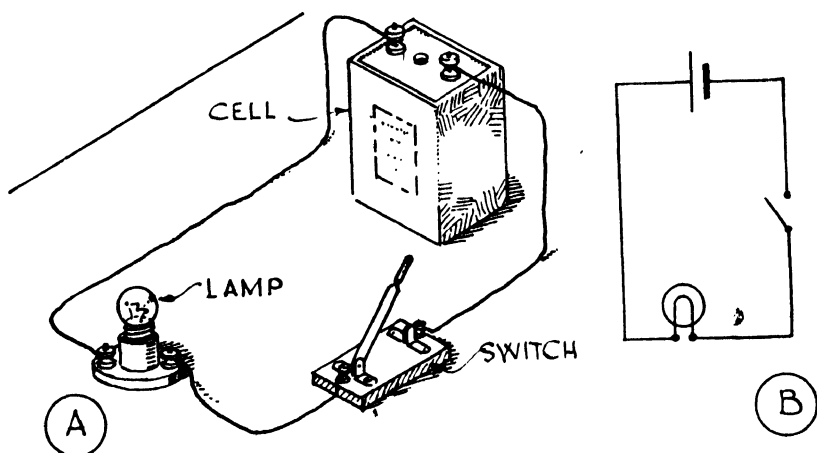


FIG. 402.—Simple Electrical Circuit.

In an *earth return* circuit one terminal of the source and one terminal of the lamp or other apparatus is connected to the earth, by being buried or alternatively by being connected to a conductor which is in turn connected to the earth. The earth is a good conductor and its resistance is negligible, so that in a very long circuit, and especially with weak current such as in telegraphy and telephony, the earth may be substituted for

one of the wires. In all ordinary work, however, an earth return is unusual. "Earthing" of an ordinary circuit is quite different; it is merely a safety device to ensure that the P.D. between any part of the circuit and the earth cannot become greater than the P.D. at the terminals of the source of supply. It is carried out by connecting one of the terminals to the earth; the switch is placed next to the other (the high-potential) terminal and then all the apparatus in the circuit is at earth potential whilst the switch is open. If the wires or apparatus are then accidentally touched current does not pass to earth through the body.

**Electrical Units.**—As in other branches of science units must be devised so as to permit of the measurement of current, resistance, etc., and to ascertain their relationship to each other.

**UNIT OF QUANTITY.**—One of the effects of an electric current (already noted on page 129 and to be treated in further detail in the next section of this chapter) is its ability to decompose certain liquids. If two copper plates are suspended in a solution of copper sulphate and a current passed from one to the other through the solution, chemical action is started and metallic copper is deposited on the surface of one of the plates. Furthermore, it is found that the mass of copper added to the plate is in direct proportion to the current and to the time throughout which the action proceeds, *i.e.* to the quantity of electricity flowing through the circuit. So exactly can this amount of copper be determined (by weighing the plate before and after deposition) that it gives an accurate means of devising a unit of quantity. The unit is called the *coulomb* and is the quantity of electricity which deposits .00033 gm. of copper. It was originally devised not by the means described but by another method which was not so exactly determinable. This accounts for the apparently illogical figure of .00033.

**UNIT OF CURRENT.**—This is a unit of velocity as distinct from quantity, in other words of quantity per unit of time. If a water pipe discharging uniformly delivers say 50 gallons and the process occupies five minutes, then the velocity or rate of flow is 10 gallons per minute. Similarly, if say .165 gm. of copper is deposited in 100 seconds the electricity is flowing at the rate of  $\frac{.165}{.00033 \times 100}$  or 5 coulombs per second.

The unit is the coulomb per second or, as it is more usually termed, the *ampere* (often abbreviated to *amp.*). The current in our example would thus be stated as one of 5 amperes, but it must be remembered that this refers not to the quantity but to the rate or "strength" of the current. For relatively weak currents the *milliampere* is used—this is one-thousandth of an ampere.



To return to the unit of quantity, we may therefore define the coulomb as 1 *ampere-second*, but the practical unit of quantity is, for greater convenience, the *ampere-hour*. Thus if, for instance, a cell is rated at 15 ampere-hours this is the quantity of electricity which it will yield—1 ampere for 15 hours, 3 amperes for 5 hours, 5 amperes for 3 hours, etc., etc. The ampere-hour is, of course, the equivalent of 3,600 coulombs.

**UNIT OF RESISTANCE.**—The unit of electrical resistance is the *ohm*, and it is the resistance offered by a column of mercury 1,063 mm. long, 1 sq. mm. in cross-section and at a temperature of 0 deg. Cent. A standard temperature must be taken because the resistance of a metal varies with its temperature, increasing with a rise, and decreasing with a fall, of temperature.

As the degree of resistance of materials varies within such wide limits (from good insulators on the one hand to good conductors on the other) it makes for convenience in practice to use the secondary units of the *megohm* (1 million ohms) and the *microhm* (1 millionth part of an ohm) respectively according to the type of material.

**UNIT OF POTENTIAL DIFFERENCE.**—The unit of potential difference is called the *volt* (hence the term voltage sometimes used synonymously with P.D. and E.M.F.). A current of 1 ampere flowing through a conductor having a resistance of 1 ohm does so by reason of a potential difference of 1 volt.

**Electrical Measurement.**—Current is measured by means of an instrument called an *ammeter* (ampere-meter), and P.D. by a *voltmeter*. There are several types of each depending upon their principle of operation; for the present it is sufficient merely to explain their manner of use. For comparison of resistances the mercury column is not convenient; instead a length of special wire is used with its ends connected to terminals, and arranged so as to be of known fixed resistance—"so many" ohms. As the length of such a wire is great it is wound in the form of a coil on to a cylinder or tube of incombustible insulating material so that its turns do not make contact with each other.

**EXPERIMENT 199.**—Use of voltmeter to measure E.M.F. of a cell.

The voltmeter shown in Fig. 403 is the usual type used in experimental work. It is mounted on a board and has two screw terminals for connecting up in the circuit. It is connected across the terminals of the cell as illustrated diagrammatically in Fig. 404 and the number of volts indicating the electrical pressure in the circuit read off from the dial. A single "dry" cell will give about 1.5 volts, whilst a fully charged accumulator cell will give approximately 2 volts.

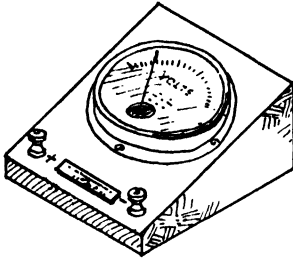


FIG. 403.—Common Type of Voltmeter.

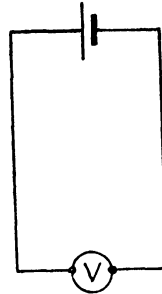


FIG. 404.—E.M.F. of Cell measured by Voltmeter.

**GROUPING OF CELLS.**—If a greater E.M.F. is required than is given by a single cell, any number of cells may be connected so that their E.M.F.s are cumulative. To accomplish this the positive terminal of one cell is connected to the negative terminal of the next, and so on, leaving the negative of the first and the positive of the last as the supply to a circuit (or *vice versa*). The cells are then said to be connected *in series*, and although the combined E.M.F.s are available—*e.g.* three identical accumulator cells would give about 6-volts—the current which the whole is capable of carrying is identical with that of a single cell.

If we require stronger current but still at the E.M.F. of a single cell we may connect all the positive terminals to give a common positive for the supply, and all the negative terminals to give a common negative. These cells are connected *in parallel*, and three cells so joined would be capable of carrying as much electricity but still at about 2-volts pressure. In both cases the group of cells constitutes a *battery*.

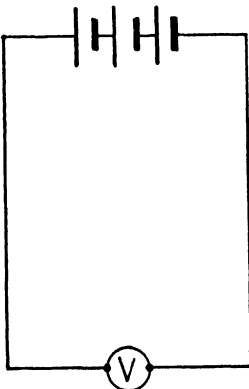


FIG. 405.—Cells "in Series."

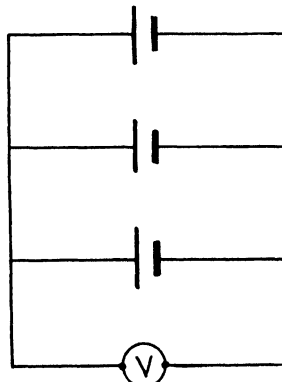


FIG. 406.—Cells "in Parallel."

**EXPERIMENT 200.**—To measure E.M.F. of cells in series and in parallel.

Fig. 405 shows three accumulator cells arranged in series in circuit with a voltmeter, whilst in Fig. 406 they are shown in parallel. Connect the cells in both ways, in each case reading the value of E.M.F. In series the reading shown will be 6-volts or thereabouts, and in parallel it will be about 2-volts as for a single cell.

**EXPERIMENT 201.**—To measure E.M.F. and current in a simple circuit.

Arrange a circuit as in Fig. 407. The battery comprises two dry or Leclanche cells in series and the lamp is a pocket torch bulb. A suitable ammeter is included in the circuit but the voltmeter is connected across the battery and is thus in parallel. The readings on both instruments will depend upon the state of the cells but if these are fresh the E.M.F. will be about 3-volts; the current will depend upon the resistance of the filament of the lamp.

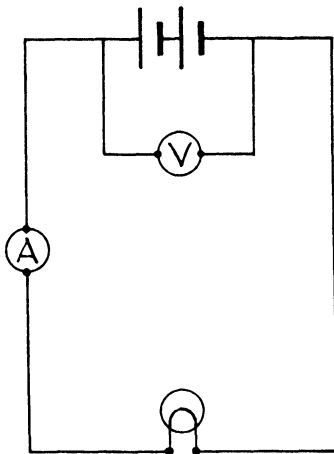


FIG. 407.—Measurement of E.M.F. and Current in a Circuit.

**RESISTANCE.**—It is often necessary—indeed, it is always advisable—to include in an experimental circuit a means of varying its resistance so as to control the current taken from the cell or other source. Such an arrangement is called a *variable resistance* or *rheostat*. One type of rheostat, rarely used nowadays, consists of a number of discs of carbon threaded on to a rod fixed in a frame and with a screw at the end for varying the pressure of contact between them. The more tightly they are compressed the lower is their resistance. A better type is the sliding

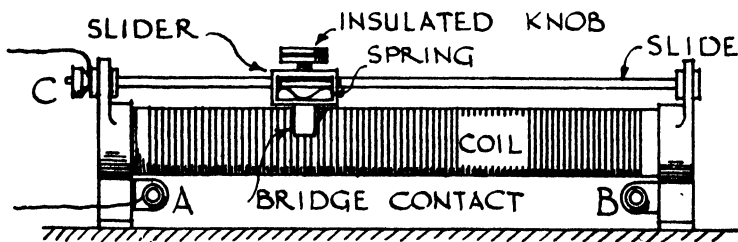


FIG. 408.—Sliding-Contact Rheostat.

contact rheostat shown in Fig. 408. A high-resistance enamelled or oxidized wire is wound on to a tube of insulating material and its ends connected to terminals A and B. When the rheostat is connected into a circuit by these terminals the whole length of the wire is included and the resistance is at its maximum. Over the coil is a square-section bar, with terminal C at one end, and along it and in metallic contact with it slides a bridge of springy metal which makes contact with the turns of wire on both sides. The sliding contact bares the outside of the turns of wire, so making electrical contact, but they are still insulated from each other by the enamel, etc. between them. When the rheostat is connected into a circuit by terminals A and C only that portion of the coil between A and the slider is included. This is shown in Fig. 409 which gives the

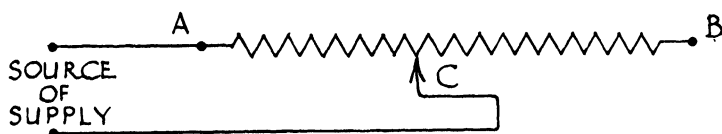


FIG. 409.—Principle of the Variable Resistance.

conventional representation. The rheostat is used in conjunction with an ammeter, the slider being adjusted until the desired current is obtained. If it is desired to vary resistance by directly known amounts, a different type of variable resistance may be used. It comprises a number of fixed resistances of such values that by manipulation any value from zero to the maximum may be obtained in steps of 1 ohm.

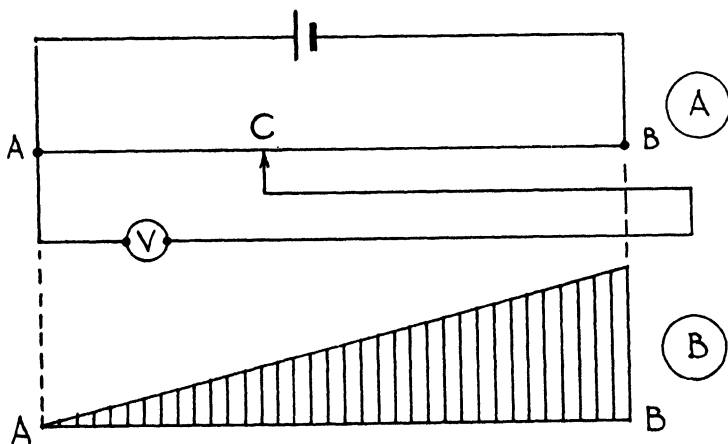


FIG. 410.—Fall in Potential along a Circuit.

**EXPERIMENT 202.**—To show the drop in potential along a circuit.

Fix a long wire of high-resistance metal to two terminals A and B (Fig. 410, A) also connected to an accumulator cell. Arrange a voltmeter as shown so that C may be connected at any desired point, and take readings of E.M.F. and length AC. It will be found that when C coincides with A the potential difference as indicated by the meter is nil, whilst when C coincides with B it is maximum. At intermediate points it will be found to be in proportion to length AC. It may therefore be shown diagrammatically as in Fig. 410, B.

This fall of potential along the wire may be compared with the fall of pressure along a horizontal water pipe as in Experiment 190, page 423.

**EXPERIMENT 203.**—To show the relationship between P.D. and current.

Connect up the circuit shown in Fig. 411 with an ammeter A, a rheostat R and a fixed resistance F.R. This last should be a high resistance wire of a metal whose resistance does not increase with rise of temperature, such as Eureka metal, and a voltmeter should be connected across it. Adjust R so that a series of different readings is obtained on A and for each note the reading of V. Allowing for experimental error it will be found that  $\frac{V \text{ reading}}{A \text{ reading}}$  is constant throughout.

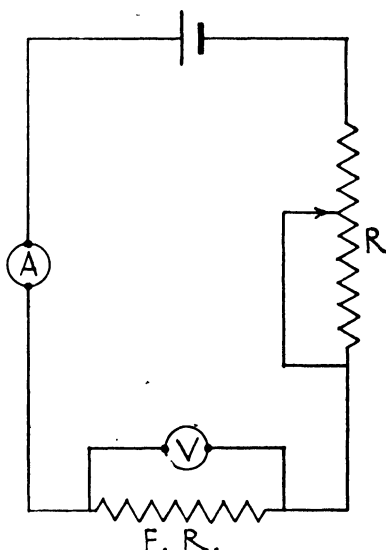


FIG. 411.—Relationship between Current and Potential Difference.

This relationship is known as *Ohm's Law*, usually stated :—*In any conductor at constant temperature the current is directly proportional to the potential difference between its ends.* Therefore

$$\frac{\text{P.D. (Volts)}}{\text{Current (Amps.)}} = R \text{ (Ohms), the resistance of the conductor.}$$

**GROUPING OF RESISTANCES.**—When several resistances are connected end to end as in Fig. 412 they are “ in series ” and their combined resistance is the sum of the separate resistances—9 ohms in the case shown.

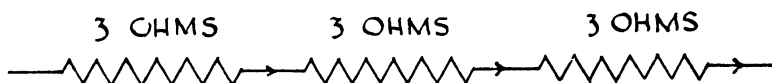


FIG. 412.—Resistances “in Series.”

In Fig. 413 the resistances are connected “in parallel” and the combined resistance is now *less than any one of the separate resistances*. This is because the current, instead of having to traverse all in turn, as in series connection, now has to split up in order to traverse all three. This is equivalent to its traversing a single thicker conductor, which, of course, would have a lower resistance. At point A the current divides into three branches, but the P.D. between A and B is the same in all three cases; therefore the current  $\frac{\text{P.D.}}{\text{Total } R} = 3 \times \frac{\text{P.D.}}{3 \text{ ohms}},$

therefore  $\frac{1}{R} = \frac{1}{3} + \frac{1}{3} + \frac{1}{3} = \frac{4 + 4 + 4}{12} = 1$ , therefore  $R = 1 \text{ ohm}.$

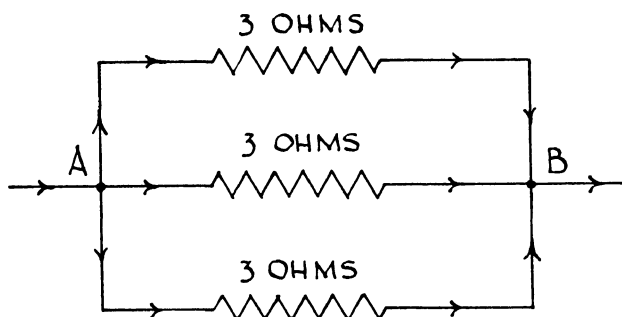


FIG. 413.—Resistances “in Parallel.”

It must be remembered that everything in a circuit, wiring, instruments, *and the liquid in the cell* (when a cell is the source), offers resistance. This liquid is a conductor and its resistance follows the same laws as do metallic conductors, depending therefore upon the type of liquid, the length of the current path (distance apart of the plates), and the size of the plates. Some of the E.M.F. of a cell is thus used up in forcing the current through the cell itself. An accumulator cell has a very low internal resistance but this can be a disadvantage in the event of its terminals being accidentally “short-circuited” by a low-resistance conductor, say the blade of a screwdriver, etc., for the combined resistance of the circuit is then negligible and too heavy a current is momentarily produced. This is bad for the plates, and it is therefore advisable always to connect to the accumulator only when all else is completed and subsequently to disconnect it first.

## 2. EFFECTS OF ELECTRIC CURRENT.

The effect of passing a current through a conductor varies with the type of conductor. It has been mentioned that a liquid conductor may suffer chemical change; this is not surprising when it is realized that atoms are put into a certain commotion in both processes, the production of current and chemical action. In such a case energy is transformed—electrical into chemical energy. The effect upon a solid conductor is twofold; heat is propagated as a result of the resistance of the conductor, and the conductor develops magnetic properties. Each of these important effects will now be dealt with in turn.

**Electric Current and Chemical Action.**—Many liquids undergo chemical change when used as electrical conductors. They are called *electrolytes*, and the process is termed *electrolysis*. The most effective electrolytes are solutions of salts or acids and water—pure water is a poor conductor. The chemical action takes place at the points where the current is transferred from and to the metallic parts of the circuit. This transfer is effected by metal plates or *electrodes* suspended in the liquid and connected to the circuit wiring. The electrode by which the current enters the electrolyte is the *anode* and that by which it leaves is the *cathode*.

The electrolysis of water by means of the water voltmeter has been described in Chapter VIII. The electrolyte is very dilute sulphuric acid and the electrodes are of platinum, oxygen being liberated at the anode and hydrogen at the cathode. It is also found that if the current is kept constant the mass of each gas is proportional to the time for which the current passes, *i.e.* to the quantity of electricity.

Sulphuric acid ( $\text{H}_2\text{SO}_4$ ) is a typical acid electrolyte, and we have seen in Chapter IX that if we replace the hydrogen by a metal, say copper, we obtain a salt, in this case copper sulphate ( $\text{CuSO}_4$ ). The  $\text{SO}_4$  is called the *acid radicle* of the salt, and if we substitute a solution of copper sulphate for the sulphuric acid as the electrolyte we get copper deposited on the cathode whilst the acid radicle appears at the anode. Both electrodes are of platinum and the cathode receives a layer or coating of metallic copper, but as platinum does not form salts the acid radicle does not combine with the anode; instead it combines with some of the water, as in the water voltmeter, and produces sulphuric acid and oxygen ( $2\text{H}_2\text{O} + 2\text{SO}_4 = 2\text{H}_2\text{SO}_4 + \text{O}_2$ ). As before the amount of copper deposited is in direct proportion to the quantity of electricity passing out of the electrolyte, hence the coulomb as the unit of quantity (see page 453).

**THE COPPER VOLTAMETER.**—Any apparatus whereby a current may be measured by the chemical action which it produces is called a *voltmeter*. In the water voltmeter the combined volumes of oxygen and

hydrogen liberated in 1 second by a current of 1 ampere is  $\cdot 1743$  c.cm. at normal temperature and pressure. If, therefore, we determine the volume of the gases liberated over a given period of time we can obtain the strength of the current in amperes. In the copper voltameter, as we have seen, a mass of  $\cdot 00033$  gm. of copper is deposited on the cathode for each coulomb of electricity, or this quantity per second for each ampere of current.

In the copper voltameter proper, the platinum electrodes are replaced by copper, and the copper cathode therefore increases in weight due to the extra copper deposited on it. But, unlike platinum, the copper anode combines chemically with the acid radicle of the copper sulphate electrolyte to form copper sulphate, so maintaining the strength of the electrolyte solution and "dissolving" copper from the anode. It is found that the mass of copper lost by the anode in this way is equal to that gained by the cathode.

In all such cases the metal (or the hydrogen of an acid electrolyte, since  $\text{H}_2\text{SO}_4$ ,  $\text{HCl}$ , etc. are solutions of hydrogen sulphate, hydrogen chloride, etc.) and the acid radicle travel in opposite directions through the electrolyte. The atoms of metal or hydrogen are charged positively, *i.e.* are deficient in electrons, and are called *ions*, and in their journey through the electrolyte they pass through an equal stream of negative ions of the acid radicle. (This latter ion is, of course, a *combination* of charged atoms.) The ions therefore reach their respective electrodes before electrical decomposition commences.

**ELECTRO-PLATING.**—Electrolysis is utilized in industry in the process of "plating" metals. Usually a coating of silver, chromium, gold, etc., is required to be applied to an article made of an inferior metal. The goods to be plated are arranged to form the cathode by suspending them in a bath containing the appropriate electrolyte, whilst the anode is usually a plate of the metal to be deposited.

Silver plating is invariably applied to goods made of "nickel-silver," an alloy of nickel, copper and zinc. The electrolyte is a mixture of silver cyanide and potassium cyanide solutions, and the anode silver. Gold plating employs a gold anode and an electrolyte composed of solutions of gold cyanide and potassium cyanide.

Chromium plating is popular because of the hardness and consequent hard wearing properties of its surface. It is generally applied to steel goods by a sequence of processes. First the article is plated with copper, then nickel is superimposed, the anode being nickel and the electrolyte a combined solution of ammonium sulphate and nickel-ammonium sulphate. Finally the chromium coating is applied, the anode being lead and the electrolyte a solution of chromic acid ( $\text{H}_2\text{CrO}_4$ ); this has



to be replenished occasionally with more  $\text{CrO}_3$  as its strength is not in this case maintained by the anode.

**THE SIMPLE ELECTRIC CELL.**—Our brief study of electrolysis has shown that electrical energy can be converted into chemical energy. It would be more correct to say chemical plus heat energy, since a certain amount of heating takes place, but the heating effect will be discussed later. Can chemical energy be similarly transformed into electrical energy? It may be shown quite simply that it can.

If we connect up an electrolytic cell (like the water voltameter) in series with a 4-volt accumulator and a switch, with a voltmeter connected across the cell, we get, when the switch is closed, a reading of the E.M.F. (Fig. 414). Upon opening the switch the voltmeter continues to give a reading, lower than before, but which gradually falls to zero. The current passing through the cell has not immediately stopped; instead the P.D. between the two electrodes has brought about a weaker current in the reverse direction. At the moment of opening the switch the two electrodes will be seen covered with bubbles of gas, which disappear slowly as the voltmeter reading declines. These are of oxygen on the anode and hydrogen on the cathode, and their gradual disappearance is due to the fact that the functions of the two electrodes are now reversed, oxygen being given up at the former cathode and hydrogen at the former anode. Thus the oxygen combines with the hydrogen bubbles to form water, and the hydrogen combines with the oxygen bubbles to form water, the chemical energy of this combination producing the E.M.F. which is registered by the voltmeter.

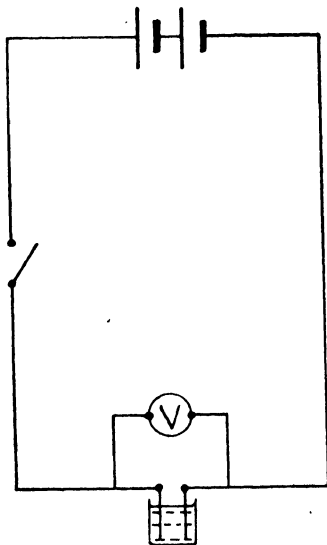


FIG. 414.—Simple Experimental Primary Electric Cell.

When chemical action results from the immersion of a metal plate in an electrolyte a P.D. arises between the two. Different metals react in this way to different degrees, and if we immerse two dissimilar metal plates we get a P.D. between each plate and the electrolyte. This apparatus is a *simple cell* and the P.D. between the plates themselves (and thus the E.M.F. of the cell) is therefore the difference between these two P.D.s. If we were to immerse two plates of the same metal we should clearly get no E.M.F.

The best pairs of metals from the consideration of E.M.F. are zinc and one of the following :—Platinum, gold, copper ; from the point of view of cost and availability zinc and copper are used. The simple cell consists of plates of copper and zinc suspended in dilute sulphuric acid, the zinc then being at a lower potential and the copper at a higher potential than the acid. If a loop of copper wire be connected to the two terminals we complete a circuit and a current flows through the wire, plates and electrolyte. This is a flow of negative electrons from the zinc to the copper via the wire, and the terminal of the zinc plate is thus marked —, the copper being positive or +. Because, however, the original idea of positive electricity flowing from + to — is retained we shall retain it here ; in fact it makes little difference since the result is the same.

**EXPERIMENT 204.**—To show polarization of a simple cell.

Fit up a simple cell as in Fig. 415 and connect a voltmeter across it by means of two short wires. Note that the P.D. is not maintained for long, but slowly disappears. Observe that both plates are covered with gas bubbles, some of them escaping to the surface of the acid. Remove one of the wires, so breaking the circuit, and note that although bubbles still escape from the zinc plate they no longer escape from the copper. Chemical action between the zinc and the acid is clearly continuing but zinc is being wasted, since this energy is not being converted into electrical energy.

Withdraw the copper plate, wipe off the bubbles, replace the plate, and observe that the E.M.F. is restored, but only momentarily. Repeat, but this time thoroughly clean the copper with emery cloth. The plate has now regained its original properties and the P.D. is maintained for the same length of time as at first.

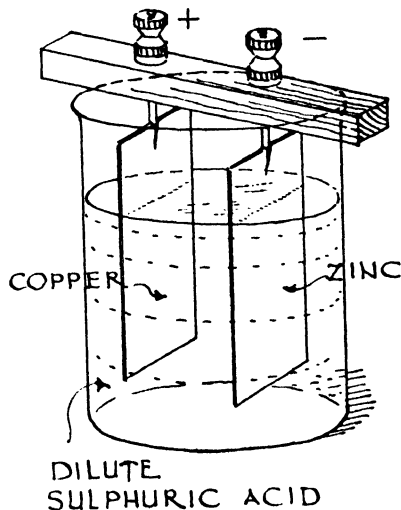


FIG. 415.—The Simple Cell.

The hydrogen bubbles (the copper is, of course, the cathode of the cell) offer high resistance, and also reduce the area of the plate exposed to the electrolyte. In addition their presence amounts to partly substituting a "plate" of hydrogen for the original copper plate. Now the P.D. between the hydrogen and the acid is greater than that between copper and acid, so that for this reason alone the E.M.F. of the cell is reduced

(the E.M.F. now being zinc-acid P.D. minus hydrogen-acid P.D.). This effect is called *polarization*, because the hydrogen forms a new pole, and it serves to apply an opposite or *back* E.M.F. The cumulative result of these three effects of the hydrogen is to reduce the E.M.F. of the cell to zero, in other words the cell ceases to function.

The simple cell is therefore unsuitable for practical use unless the accumulation of this hydrogen can be prevented. This is done in different ways in the three types of primary cell to be described.

**PRIMARY CELLS.**—In the *bichromate cell* the hydrogen is made to combine chemically with an oxidizing agent or “depolarizer” (usually potassium bichromate— $K_2Cr_2O_7$ ) added to the electrolyte, dilute sulphuric acid, the plates being zinc and carbon. In spite of the high E.M.F. and low internal resistance it is now obsolete, because of the necessity to remove the zinc plate when the cell is not in use, if wastage is to be avoided.

The *Daniell cell* has zinc and copper poles with dilute sulphuric acid as the electrolyte. The outer containing vessel is of copper and serves as the copper plate. This contains copper sulphate solution and in this is immersed a porous jar containing the acid and the zinc plate. In action the hydrogen resulting from the interaction of the zinc and acid passes through the porous jar but before reaching the copper interacts with the copper sulphate, metallic copper being deposited on the copper plate instead.

$$(Zn + H_2SO_4 = ZnSO_4 + H_2)$$

$$(H_2 + CuSO_4 = H_2SO_4 + Cu)$$

It will be seen that the copper sulphate solution must be kept up to strength and this is done by keeping a supply of copper sulphate crystals suspended in it. This cell also is obsolete because of the gradual diffusion through the porous jar, with detrimental results to the zinc.

Both these types of cell were invaluable for laboratory purposes before the perfection of the secondary cell, but had to be wholly or partly dismantled between periods of use.

The *Leclanche cell* is a type of primary cell which has retained its popularity, especially in the form of the “dry” cell. The normal Leclanche comprises a glass container holding the electrolyte, ammonium chloride solution. In this is immersed the negative pole in the form of a zinc rod, and a porous jar containing the positive pole, a plate of carbon packed with a powdered mixture of manganese dioxide and carbon. In this cell the porous jar serves merely to contain this mixture, not to separate two different liquids as in the Daniell cell. The powdered carbon increases the effective surface of the positive pole, so reducing the internal resistance, and also prevents the manganese dioxide, which is the depolarizer, from becoming caked, and increases its conductivity. When the

circuit is closed the zinc and electrolyte interact as follows :— $\text{Zn} + 2\text{NH}_4\text{Cl} = \text{ZnCl}_2 + 2\text{NH}_3 + \text{H}_2$ . The liquid slowly becomes zinc chloride, ammonia is given off, some of which dissolves whilst the remainder escapes as gas through the vent. The further reaction is :— $2\text{MnO}_2 + \text{H}_2 = \text{Mn}_2\text{O}_3 + \text{H}_2\text{O}$ . The hydrogen, as it collects on the carbon, is oxidized by the manganese dioxide to form another oxide of manganese and water. This action is very slow, as the dioxide is not soluble, and in continuous use is not sufficiently rapid to prevent polarization altogether. Thus the E.M.F. of the cell falls slowly and the accumulation of hydrogen increases the internal resistance, but in between periods of use the cell returns to normal. It is thus a useful type of cell for intermittent use.

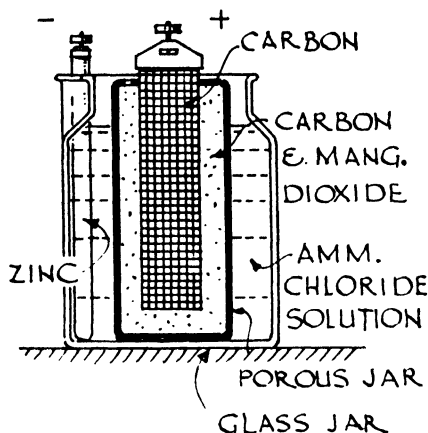


FIG. 416.—The Leclanche Cell.

In its "dry" and "inert" forms the cell usually comprises a carbon rod surrounded by a thick layer of paste made up of manganese dioxide and carbon, together with ammonium chloride and gum water. This is surrounded by the electrolyte, ammonium chloride, made into a paste with gum tragacanth and water. The outer container is made of zinc, forming the negative pole, covered with paper or cardboard. The contents are secured by a covering of pitch through which a small vent passes to enable gas to escape. The "inert" type has in addition a corked inlet through which water is introduced to moisten the paste before putting the cell into commission. Each cell gives about 1.5 volts, and for a higher E.M.F. several may be made up in series in a common outer container such as for pocket torches, radio batteries, etc.

**LOCAL ACTION.**—If commercial zinc is used for the negative pole of a cell it is acted upon by the acid whether a current is flowing or not, and this is a serious disadvantage. This is because it contains impurities such as lead, iron and carbon, and when such a plate is immersed in the acid these particles, in conjunction with the pure zinc in the plate, form a

great number of minute cells. This involves disintegration of the zinc, even when the cell is not in use, and the liberation of hydrogen at the particles of lead, etc., each of these forming a positive pole. This effect is called *local action* and can be prevented by the use of pure zinc, which is not acted upon by the acid except when the cell is giving a current. Pure zinc is too costly, however, for this purpose, so instead commercial zinc is "amalgamated." This consists of thoroughly cleaning the zinc and then rubbing it with mercury so as to form a coating of amalgam of mercury and zinc. The mercury does not dissolve the impurities as it does zinc, but merely forms a covering film, protecting them from the action of the acid; at the same time the amalgam film supplies pure zinc to the acid.

The Daniell cell is subject to local action, unless the zinc is amalgamated, but the Leclanche is not affected to any extent because of the different nature of the electrolyte.

**SECONDARY CELLS OR ACCUMULATORS.**—The primary cells are so called because their electrical energy is derived from chemical energy produced in the cell by direct chemical action between its constituents. A secondary cell or accumulator, or as it is sometimes called a *storage cell*, depends upon some external source of energy. Its electrical energy is derived also from chemical energy but this is put into the cell as a result of electrical energy supplied to it. It therefore does not store or accumulate electricity but chemical energy which in use is re-converted into electricity.

**EXPERIMENT 205.**—An experimental secondary cell.

Connect up the circuit shown in Fig. 417 with a 4-volt accumulator as the source of supply. The cell is similar to the simple cell shown in Fig. 415 but the plates are of clean sheet lead (5-lb. or 6-lb. roofing lead) kept about  $\frac{1}{4}$ -in. apart by wood strips, and the electrolyte is a 1 : 4 sulphuric acid solution. Close switch A and allow a current of about 1 amp. to flow for, say, ten minutes. Note the formation of gas bubbles especially on the negative plate; note also that the positive plate assumes a chocolate-brown colour. The voltmeter gives no reading since it is not included in the circuit.

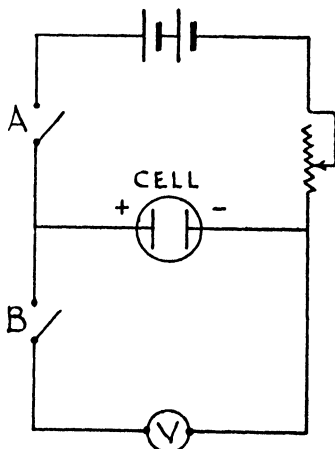


FIG. 417.—Simple Experimental Secondary Cell.

Now open switch A and close switch B. The voltmeter immediately gives a reading of about 2-volts, but then slowly falls back to zero. This current is not due to the accumulator because this is now not in the circuit, switch A being open. It must therefore be due to back E.M.F. from the cell. Now, as both plates are of the same metal, lead, we know that the cell can generate no E.M.F. directly—it is therefore a secondary cell and the plates must thus have been changed chemically during the time switch A was closed.

Whenever a current is passed through an electrolyte, chemical action takes place at the electrodes. If the products of this chemical action remain available (*i.e.* do not escape as gas, etc.) and the direction of the current is reversed, the former anode now becomes the cathode, and *vice versa*, and the chemical action is now reversed. In Experiment 205 the electrical energy put into the cell produces chemical energy which causes polarization. The cell now has a store of potential chemical energy when disconnected from the supply, and this is re-converted into electrical energy upon connecting a conductor across its plates.

The high E.M.F. available in the present case is due to the exceptional properties of lead and dilute sulphuric acid in retaining the products of the initial chemical action. These products must not only be retained, they must also be good conductors so as to be able to continue to take part in the action of the cell. At the anode (positive plate) oxygen is liberated and for this to be retained the anode must be capable of being *oxidized*. At the cathode hydrogen is liberated and for this to be retained it must have something to combine with. Hydrogen does not react with metals, but if the cathode is a metallic oxide the hydrogen can, by *reduction*, convert it to a lower oxide or to the metal, by combination with the oxygen to form water.

Lead is capable of forming a number of oxides, chief of which are :— Suboxide— $\text{Pb}_2\text{O}$  (grey), oxide— $\text{PbO}$  (yellow), tetroxide— $\text{Pb}_3\text{O}_4$  (red), dioxide— $\text{PbO}_2$  (brown), and pentoxide— $\text{Pb}_2\text{O}_5$  (black). In the lead-acid secondary cell several of these oxides are involved. Starting with an anode of lead its surface, as oxidation proceeds during charging, becomes in turn  $\text{Pb}_2\text{O}$ ,  $\text{PbO}$ , etc. Similarly the cathode, already oxidized, suffers the reverse of this change—to Pb. After this stage has been reached the oxygen and hydrogen escape at the anode and cathode respectively and there is no further storage of energy. During discharge reduction and oxidation respectively take place, with the release of electrical energy, but only until both plates have reached the stage of  $\text{PbO}$  (strictly  $\text{PbSO}_4$  by combination with the  $\text{SO}_3$  of the acid—see next paragraph) this is because further oxygen, to produce the higher oxides, is only taken up by the lead under the influence of applied energy. Higher oxides than  $\text{PbO}$  are all unstable and this is the reason.

In this state (both plates PbO) the cell is fully discharged, and upon re-charging the oxidation and reduction now go through the stages—anode PbO, PbO<sub>2</sub>, etc., and cathode PbO, Pb<sub>2</sub>O and Pb—after which the gases escape and the cell is fully charged. The anode is the positive during charging and the cathode the negative. In its fully discharged state lead sulphate is formed by the interaction of the PbO and the acid—thus  $\text{PbO} + \text{H}_2\text{SO}_4 = \text{PbSO}_4 + \text{H}_2\text{O}$ —and this forms a non-conducting coating on the plates. If the cell is re-charged fairly soon the sulphate disappears, but if allowed to remain discharged the sulphate hardens and obstructs re-charging, so ruining the cell.

The acid is, of course, subjected to changes during these processes; during re-charging it becomes more concentrated by the “absorption” of SO<sub>3</sub> from the sulphate, and during discharge it becomes more dilute by the loss of this SO<sub>3</sub> to form the sulphate. Its S.G. is thus a guide to the state of the cell at any time; when fully charged it should be 1.25, and at the PbO stage it has fallen to 1.18. (The voltage has meanwhile fallen to 1.8.) The cell should therefore be re-charged before having reached this point, so as to prevent excessive sulphation.

The experimental accumulator (Experiment 205) was very rapidly charged and just as quickly discharged. This was because of the small area exposed to the action of the acid, and also because the cell is insufficiently “formed.” To increase the area a number of positive and negative plates are arranged alternately in the containing vessel, spaced by strips of insulating material. In addition the plates are “formed”—by a slow and expensive process of alternately charging and discharging the lead is changed from the dense, compact metal to a condition like that in Experiment 13, page 16, with an open, porous surface which offers greater area. To reduce the cost and labour of forming, the plates may be ribbed or otherwise patterned, with the same object of a gain in surface area, or instead they may be in the form of lead grids filled in with a “paste” of lead oxide (PbO).

**The Heating Effect of Electric Current.**—The simple circuit given in Fig. 402, page 452, includes a small lamp which lights up when the switch is closed. This shows that the current flowing through the filament of the lamp causes it to become so hot as to give off light. The same lamp will light up when connected in circuit with a simple cell, but in this case it will be seen to fade quickly to a dull glow owing to polarization.

**ELECTRICAL ENERGY AND HEAT.**—Just as in mechanics kinetic energy is converted into heat energy by friction, so the work done in impelling electricity through a conductor appears as heat. The unit of

this work is the *joule*, and is the work necessary to send one coulomb between two points between which there is a P.D. of one volt. Thus :—

$$\begin{aligned}\text{Work done} &= \text{Potential Difference} \times \text{Quantity of Electricity ; or} \\ \text{Joules} &= \text{Volts} \times \text{Coulombs.}\end{aligned}$$

In other words the joule is the electrical energy converted into heat when a current of 1 ampere is passed through a resistance of one ohm for one second.

It was shown by Joule (from whom the unit takes its name) that, by passing a known constant current through a wire of known resistance immersed in a known mass of water in a calorimeter, the quantity of heat produced in the wire is proportional to :—

- (a) The square of the current (*e.g.* four times the heat for twice the current) ;
- (b) The resistance of the wire (*e.g.* twice the heat for twice the resistance) ;
- (c) The time during which the current continues (*e.g.* twice the heat for twice the length of time).

It has also been shown that the quantity of heat produced by  $x$  joules of electrical energy, equal to (current<sup>2</sup>  $\times$  resistance  $\times$  time), is  $\frac{x}{4.2}$  calories ; or 1 calorie (heat energy) = 4.2 joules (electrical energy), and as 1 calorie is also equivalent to 3.1 ft.-lb. (mechanical energy) therefore 1 joule = .737 ft.-lb.

It is thus possible not only to calculate the quantity of heat generated in a circuit, but conversely to calculate the strength of a current by measuring the heat given up.

**ELECTRIC LIGHTING.**—In the electric incandescent filament lamp the light is obtained by the filament becoming heated to incandescence by the passage of the current. The filament must be capable of withstanding, without melting or volatilizing, temperatures well above that required to give incandescence. The most successful early lamp had a filament of carbon, but this has been superseded by the more efficient tungsten. Tungsten is a metal with an extremely high melting point, and it can be drawn into very fine wire, but owing to its low resistance a much greater length must be used. The manner in which the filament is arranged and supported in the glass bulb is the only real difference between the various types.

The bulb of the carbon filament lamp had to be exhausted of air to prevent oxidation. Tungsten filament lamps may also be of the vacuum type, but in this case the reason is rather to prevent loss of heat to the glass by convection. This advantage, however, is outweighed by the fact that the metal volatilizes at a lower temperature when in vacuo, and it is for



this reason that modern lamps are gas-filled. The gas must be incapable of chemical combination with the hot filament, *e.g.* nitrogen or argon, and to reduce the heat loss the filament is not in the form of a plain wire but is a continuous coil of small diameter. This reduction in heat loss is so marked, and the increase in lighting efficiency so considerable, that some lamps now have the filament in the form of a coil of finely coiled wire—the “coiled coil filament.”

In recent years non-filament lamps have been used extensively, mainly for advertising and display purposes. These are known as discharge tubes. In any circuit the current can be made to “jump” across a small gap in the wiring provided that the electrical pressure is sufficiently high. It does so as a spark, and in the case of the sparking plug an E.M.F. of about 10,000 volts is necessary to spark across a gap of only about  $\frac{1}{80}$ -in. This is because the explosive mixture in the cylinder, which it is the function of the spark to ignite, is under pressure, and the higher the pressure the higher the E.M.F. required. Conversely, in a rarified atmosphere the E.M.F. required is greatly reduced, or alternatively the high E.M.F. will discharge across a much wider gap. Discharge tubes and lamps are similar in principle but instead of being arranged to give individual sparks at intervals, as in the spark plug, the discharge is continuous. They work with a very high E.M.F. and in addition contain very rarified gas according to the colour of light required. Mercury vapour gives a blue light, neon gas gives red, sodium vapour gives a distinct yellow, magnesium vapour green and carbon dioxide white light respectively.

Certain of these discharge lamps have been used for street and factory lighting, notably the mercury vapour type, but a still more recent development is “fluorescent” lighting. The interior surface of the lamp or tube is coated with a substance which becomes luminous, giving a light approximating to daylight, and which is diffused by reason of the large uniformly illuminated surface. This type of lighting has a great future in architectural lighting schemes.

**ELECTRIC HEATERS AND FUSES.**—We have seen earlier that the electrical energy spent in overcoming the resistance of a conductor is converted into heat energy, and that advantage is taken of this to produce light in the filament lamp. In this case the heat produced at the same time is unwanted, but in the case of a heater it is primarily the heat which is required, and all that is necessary is to choose a conductor having a suitable degree of resistance. It is usually a nickel-chromium alloy because this has been found also to withstand high temperatures in air without suffering excessive oxidation. In addition its resistance is almost constant at all temperatures, whereas that of a pure metal increases in proportion to rise of temperature. The heating element is in the

form of coiled wire carried on a support of insulating and incombustible material such as porcelain.

A "fuse" is a device for protecting a circuit against excessive current such as might otherwise cause damage. In its usual form it comprises a short length of wire mounted on porcelain and through which the current must pass before being supplied to the circuit in question. It must have a low melting point, and its diameter and length are such that a current slightly in excess of that normally required in the circuit is sufficient to cause it to melt and so break the circuit. A thin wire of copper is generally preferred to a thicker wire of lower conductivity and melting point such as tin or lead-tin alloy, since melting may take place violently and the molten metal be scattered. It may even volatilize and form a conducting surface on the porcelain mount, so defeating its own object.

**Magnetic Effect of Electric Current.**—This is perhaps the most important effect since it is the one upon which electric generators and motors depend for their action, the one being the means of producing the cheapest and most reliable source of commercial supply and the other the only practical means of converting electrical into mechanical energy on a large scale. The presence of this magnetic effect may be demonstrated as follows :—

**EXPERIMENT 206.**—To show the magnetic effect of a current-carrying wire.

Place on the table a small compass needle (Fig. 418) and support over it a length of about 4-ft. of copper wire so that a short length in the centre is straight and in line with the axis of the needle. Now connect the two ends of the wire to the terminals of a cell, the S. end to the positive and the N. end to the negative respectively. The needle will be deflected anti-clockwise, its ends remaining in their new positions whilst the current is flowing at the same strength. Upon disconnecting the ends of the wire the needle resumes its former direction, but upon reversing the direction of the current by changing over the terminals the needle is again deflected, but this time in a clockwise direction.

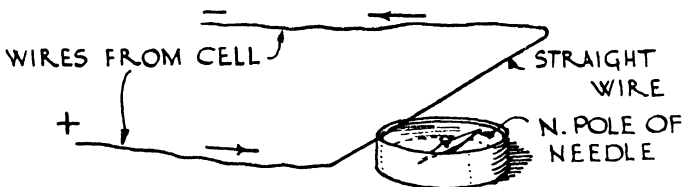


FIG. 418.—Magnetic Effect of Wire carrying a Current.

The principle of this experiment is utilized in some types of current-indicating and measuring instruments.

**MAGNETS.**—The compass needle used in Experiment 206 is a magnetic compass, a form of artificial magnet. A natural magnet is a piece of

"magnetite"—tri-ferric tetroxide,  $\text{Fe}_3\text{O}_4$ . At a very early date it was discovered that some specimens of magnetite possessed the property of attracting other magnetite as well as certain metals, notably iron; these were called "lodestones" from their use in indicating the north to mariners. An artificial magnet is a steel bar, either straight or "horseshoe," which has been magnetized by stroking with a lodestone or another magnet, or else by electrical means.

If a straight bar magnet be suspended so as to be able to rotate freely in a horizontal plane it will assume a direction almost north to south. The end pointing to the north is the N. pole and that pointing to the south the S. pole of the magnet, and if the magnet be turned to point in any other direction it will revert to its original direction when freed. Further, if the N. pole of a second magnet be brought near to the N. pole of a magnet so suspended the latter is repelled, and if the S. pole of the second magnet be brought near to the S. pole of the first this is similarly repulsed. But if, instead, the poles are brought N. to S. or S. to N. the pole of the suspended magnet is attracted. Thus *like poles repel—unlike poles attract*.

The fact that a suspended magnet, or a compass needle, assumes its N. to S. position is due to the fact that the earth itself behaves as a magnet—the regions around its north pole attracting the N. pole of the magnet, and *vice versa*. Note that this apparently contradicts the rule given in the previous paragraph, but the N. pole of the magnet is more correctly its *north-seeking* pole, and the northern regions of the earth behave as the *south* pole of the earth magnet—and *vice versa*.

The phenomenon of magnetism is explained as a result of the arrangement in a definite order of the molecules of the magnet. In a piece of ordinary iron, for instance, the molecules are "held" by inter-molecular force more or less uniformly from all directions. Each molecule is in effect a miniature magnet but their magnetic axes are in all directions. The effect of magnetization is to turn the molecules so that all lie in the same direction, this being governed by the method adopted, and the power of the magnet to attract or repel is the cumulative force of its molecules on those of the body acted upon. The degree of magnetization depends upon the degree to which the molecules have reacted, those at the surface of the magnet clearly being more easily affected than those in the interior. A laminated magnet, in which each lamina is magnetized independently before assembly, is thus more likely to have stronger magnetic properties than a solid one of similar dimensions.

**EXPERIMENT 207.**—To demonstrate magnetic induction.

Clamp a straight bar magnet vertically and bring a small piece of steel plate up to its lower pole; the steel is at once attracted and

held. Test the lower end of the plate for polarity (by observing its effect upon a compass needle) and it will be found to be the same as that of the lower end of the magnet. Now bring a second and smaller piece of steel up to the first and it will be attracted and held (if the first piece is not too heavy for the strength of the magnet). Its lower end now shows the same polarity. Continue with a smaller and lighter object such as a nail, and the polarity will still be as before.

Now hold the uppermost piece of plate and gently detach the magnet. Some of the lower pieces will remain attached. Each has become magnetized by *induction*, and if the upper end of each be tested it will be found to have a polarity opposite to that of its lower end—each is a magnet, although not a very strong one, and its newly acquired magnetic properties are soon lost.

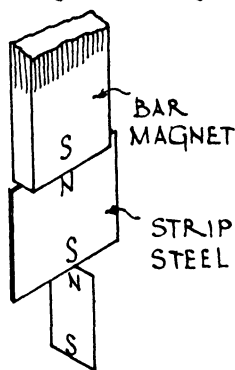


FIG. 419.—Simple Magnetic Induction.

**MAGNETIC FIELDS.**—The *field* of a magnet is the space surrounding it in which the force exerted by it can be detected. If a magnet is laid flat and covered by a piece of stiff card, dry iron filings sifted over the card arrange themselves in a series of definite curved lines. These correspond to *lines of force* which constitute the combined field due to the earth as well as to the artificial magnet. Fig. 420 shows maps of various magnetic fields—these are diagrammatic and the lines represent the lines of force in a horizontal plane as plotted by means of small compass needles. This method enables the direction of the lines of force to be determined, this being impossible by the iron filing method—besides which the friction between the filings and the card is considerable. It will be seen that the lines of force appear to proceed from the N. pole and to re-enter the magnet at the S. pole. At considerable distance from the magnet the lines of force are clearly those due to the earth (a horizontal map of the earth's field comprises a series of parallel straight lines running N.—S.) but these are distorted by the presence of the magnet. In all cases the spaces marked X are areas in which the effects of the magnet and the earth neutralize each other. A small compass needle placed at any of these *null points* will come to rest in any position.

**ELECTRO-MAGNETIC FIELDS.**—Experiment 206 showed that there is a magnetic field underneath a wire that is carrying a current, and by moving the compass needle to positions on both sides of the wire, and above it, it may also be shown that the magnetic field entirely surrounds the wire. It was also seen from this experiment that the wire only exhibited the magnetic effect *whilst the current was flowing*.

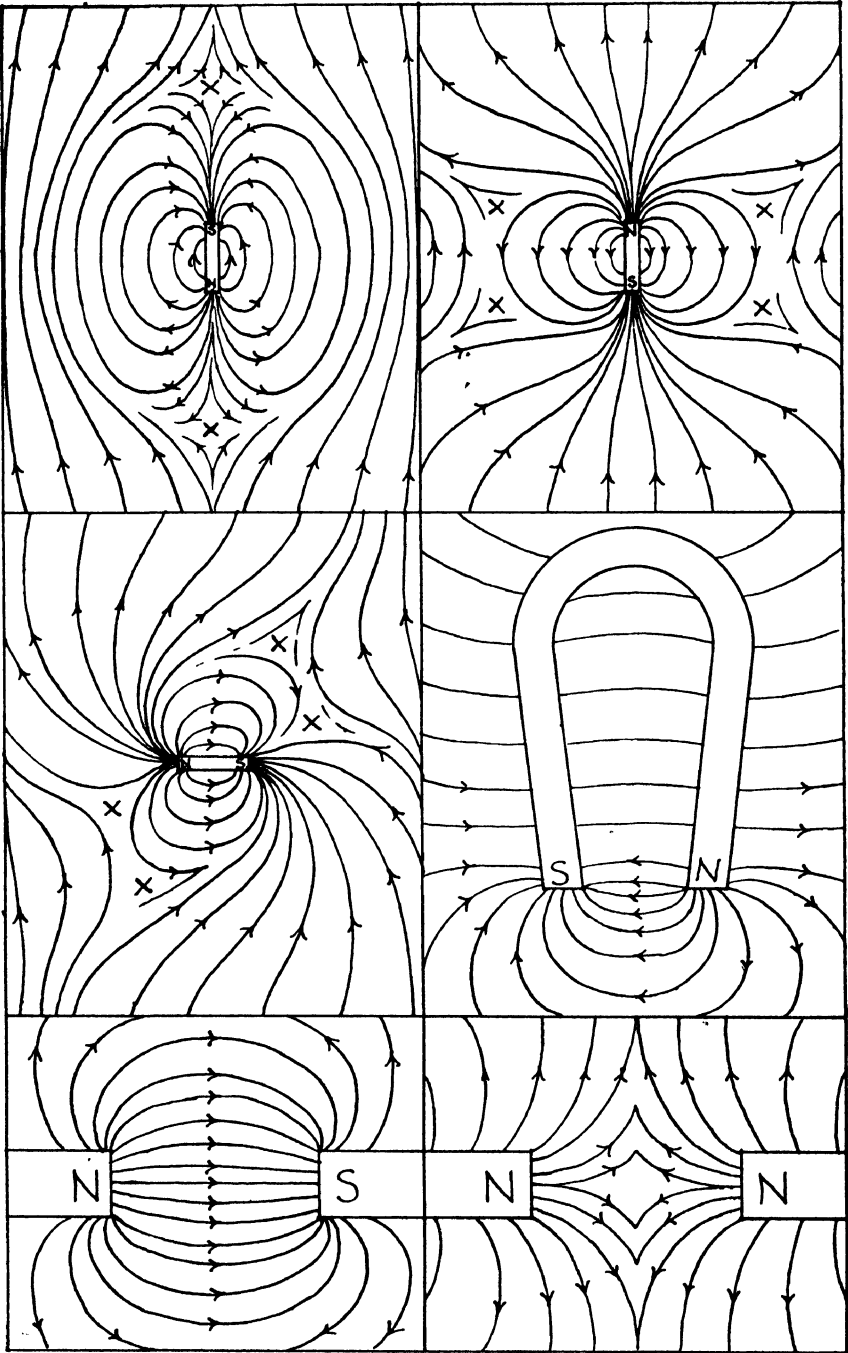


FIG. 420.—Magnetic Fields.

**EXPERIMENT 208.**—To show the magnetic field due to electric current in a straight wire.

Fix horizontally a square of cardboard which has had a small hole bored through its centre. Pass through the hole a straight vertical length of stout copper wire and sprinkle on the card a few dry iron filings (Fig. 421). Now connect the ends of the wire by other wires to the source of supply (a current of about 30 amps. is needed, but if this is not available compass needles should be substituted as these are affected by much weaker currents), and lightly tap the card. The filings are seen to arrange themselves in concentric circles around the wire. By placing a compass needle on the card the direction of the lines of force may be determined, and will be found to be *clockwise when viewed in the direction of the current*—and *vice versa*.

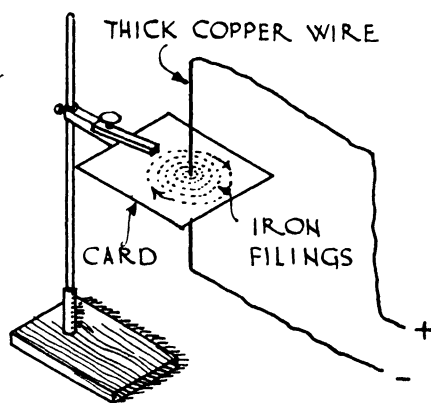


FIG. 421.—Magnetic Field of a Straight Wire.

**EXPERIMENT 209.**—To show the magnetic field due to electric current in a circular coil.

When a wire is bent into circular form and passed through a card and a current passed through the wire, the lines of force, as might be expected from the previous experiment, are as shown in Fig. 422. Observe the polarity.

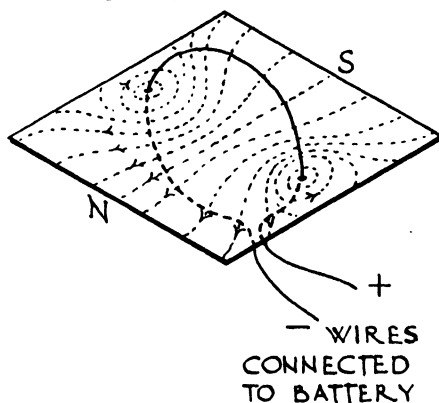


FIG. 422.—Magnetic Field of a Circular Coil.

**EXPERIMENT 210.**—To show the magnetic field due to electric current in a helix.

Repeat the experiment with the wire threaded through the card as in Fig. 423. The magnetic field will be seen to resemble that of a straight bar magnet, and such a helix might thus be expected to act as a magnet.

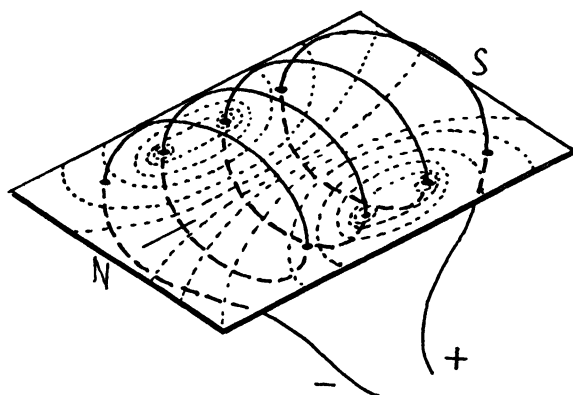


FIG. 423.—Magnetic Field of a Helix.

**EXPERIMENT 211.**—To show the effect on an iron core of a helix carrying a current.

Take a short length of narrow bore glass tubing and an iron nail or similar length of soft iron rod which will easily slide into the tube. Fit at each end of the tube a disc of cardboard so as to convert it into a spool and wind on it several layers of thin insulated copper wire as in Fig. 424. Place the nail or rod on the table vertically and partly inside the tube, and connect the ends of the coil in series with a switch and a 6- or 8-volt battery, connected as shown.

Close the switch, and note how the nail is drawn up into the tube. Reopen the switch and the nail is released, to fall to the table again.

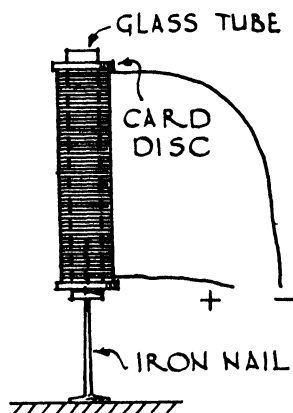


FIG. 424.—Effect of Iron Core.

Such a coil is called a *solenoid*, and many applications of this principle, in which a small mechanical force has to be exerted by distant control, come readily to mind. The stronger the current, and the greater the number of turns of wire, the greater the force exerted.

**ELECTRO-MAGNETS.**—The effects of inserting a soft iron core into a helix of wire is greatly to strengthen the magnetic field. This is because the magnetism acquired by the iron through its being placed in the path of the internal lines of force augments that of the helix itself. Such a contrivance is an *electro-magnet*, and the soft iron core is, like the helix itself, only magnetized for so long as the current is flowing. If the core is of steel it becomes permanently magnetized, and more powerful permanent magnets may be made by this means than by stroking with another magnet. The great advantage of the soft iron core is that the magnetism is under perfect control by merely operating a switch, whether used for lifting iron and steel in engineering works, or for operating mechanisms such as indicators, etc.

If the iron core of a solenoid is made to take the form shown in Fig. 425 a strong magnetic field is produced in the air gap, most of the lines of force crossing the gap between the two poles, whilst in the *toroid* (Fig. 426) the magnetic field is entirely confined within the windings.

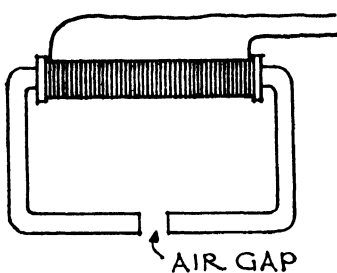


FIG. 425.—Solenoid with Air Gap.

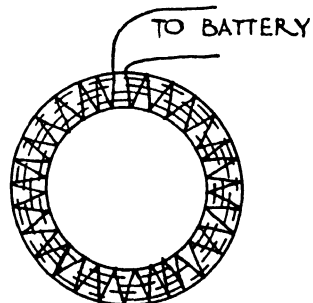


FIG. 426.—Magnetic Field of a Toroid.

Interesting applications of the principle shown in Fig. 425 are the electric bell and buzzer. Fig. 427 shows such an arrangement in diagrammatic form. A is the striker fixed to the end of a flat spring which can vibrate about its other (fixed) end. To the spring is attached an iron plate or armature B, and a subsidiary flat spring C, which presses against an adjustable contact D. Facing the armature and separated by an air gap is a solenoid or (as in the example shown) a horse-shoe electro-magnet with two windings in series. The connections are as shown, and upon closing the switch the circuit is closed and current flows through the two coils and back to the battery via the striker spring, the subsidiary spring and the contact screw. But the effect of the current passing through the coils is to set up a magnetic field through the iron core and the armature via the air gaps, as suggested by the dotted lines in the diagram. This results in the armature being suddenly attracted and the bell being struck.



At the same moment, however, contact between spring C and screw D is broken, and the circuit thereby interrupted, whereupon the magnetic field is destroyed and the armature no longer held to the iron core. The striker spring is now free to withdraw the armature and striker and in doing so again makes contact between C and D, so completing the circuit again. The action thus proceeds for so long as the switch remains closed.

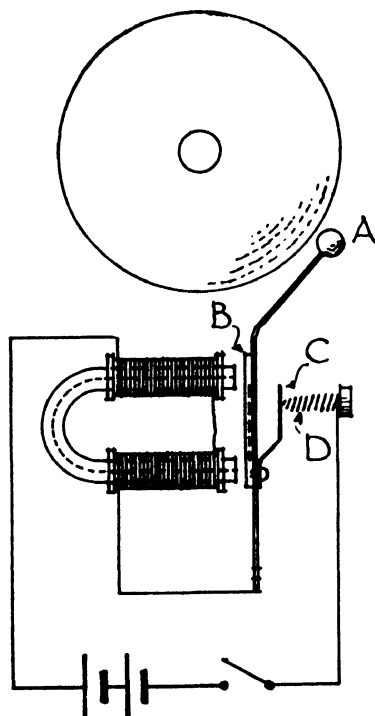


FIG. 427.—The Electric Bell.

### 3. ELECTRO-MAGNETIC INDUCTION.

The fact that magnetism can be produced by means of an electric current has been shown ; it will now be shown that the reverse is also true—that electric current may be produced by magnetic means. (Strictly, an E.M.F. is produced and this causes the current to flow.)

**EXPERIMENT 212.**—To produce electric current by means of a magnet.

With thin, insulated copper wire make a coil in the form of a close helix, winding the wire finally around the turns so as to hold them together. Connect the two ends to the terminals of a galvanometer (a very sensitive ammeter, such as was used in connection with the thermopile in Experiment 177). Clamp vertically in a stand a permanent bar magnet, so that its N. pole is uppermost (Fig. 428, A).

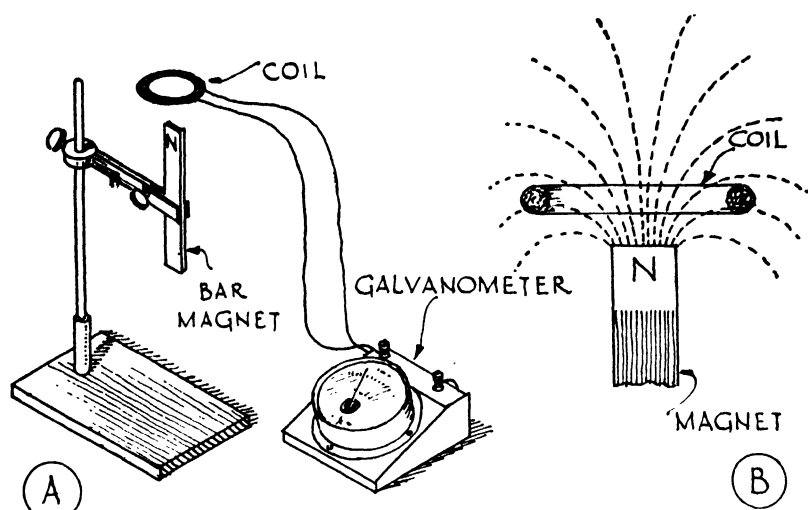


FIG. 428.—Current produced by Magnet and Coil.

Now lower the coil *gently* over the magnet. The galvanometer needle is unlikely to be affected. Withdraw the coil *gently* and again lower it over the magnet, this time *smartly*. The needle now registers a momentary current. Withdraw the coil *smartly* and another momentary current is registered, but the deflection of the needle is now in the opposite direction. (The instrument must be one having a central zero.)

Next bring the coil up rapidly over the S. pole of the magnet. The needle deflection is in the same direction as when withdrawing the coil from the N. pole. Remove the coil, and the deflection is momentary and in the opposite direction, *i.e.* identical with that when lowering the coil over the N. pole.

Now remove the magnet and fix the coil in its place. Repeat the experiment by thrusting in and withdrawing the magnet, first its N. and then its S. pole. The results are as before, and this shows clearly that the current is only produced whilst the coil and the field of the magnet are in motion *relative to each other*.

It will be shown in the next experiment that, other things being equal, the current generated increases with increase of the relative motion of the coil and the magnet. Such a current is said to be *induced*. Let us now see whether an electro-magnet can be used in place of the permanent magnet.

**EXPERIMENT 213.**—To demonstrate electro-magnetic induction.

In Fig. 429, A is a "cylindrical" coil of many turns of fine insulated copper wire wound on to a cardboard reel. B is a similar coil composed of fewer turns of thicker wire, and of such diameter

as to slide easily inside coil A. G is a galvanometer, C a cell to provide the current for coil B, and S is a switch in series with the cell and coil B.

With the switch closed coil B is converted into an electro-magnet, and by sliding it into, and withdrawing it from, coil A identical results are obtained to those resulting from Experiment 212. In addition this apparatus enables us better to verify that the faster the relative movement the greater is the movement of the needle, and so the stronger the current induced in coil A.

Next support coil B near to coil A (in about the position shown) and open the switch; an immediate momentary deflection of the needle, in the same direction as when the coils were separated, is observed. Close the switch and a similar sudden deflection occurs, but in the opposite direction, this being the same as when B was introduced into A.

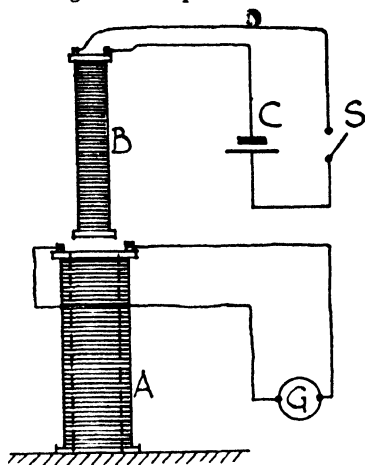


FIG. 429.—Electro-Magnetic Induction.

**THE TRANSFORMER.**—Imagine the lines of force of coil B in the last experiment, or of the permanent magnet in Experiment 212. When, in either case, the magnet is moved in or out of the fixed coil, lines of force of the magnet move *across* the wires forming the coil, or “cut” them. Similarly when the coil is moved over the fixed magnet it “cuts” the lines of force, and it is this which produces the E.M.F. (Fig. 428, B). In Experiment 213 the E.M.F. induced by merely operating the switch with the coils stationary is generated by the sudden appearance and disappearance of the field of the magnet causing some of its lines of force to cut the coil.

If in Experiment 213 coil B had been wound around an iron core the current induced in coil A would have been much stronger, since B would have been a stronger electro-magnet, with more operative lines of force over a given area of A. It will be remembered that in the toroid type of coil (Fig 426) the magnetic field is enclosed within the windings; the arrangement shown in Fig. 430, in which each coil is, as it were, a portion of a single toroid and with a common iron core, may therefore be expected to give good results. This was the type used by Faraday when he discovered the principle of electro-magnetic induction in 1831.

The electric *transformer* is an appliance used to change or transform a supply of electric current from one voltage to a higher or lower one. The principle upon which it operates is that of Fig. 430 where the primary coil is connected to the original supply and the induced current is set up in the secondary coil, and so throughout its circuit, by the "make" and "break" of the primary current (the opening and closing of the switch in Experiment 213). The voltage ratio depends upon the ratio of the number of turns on the two coils. For instance, if the primary coil has 100 turns and the secondary has 500, then a primary applied E.M.F. of 4-volts induces an E.M.F. of 20-volts in the secondary. But as more energy cannot be taken out than has been put in, the secondary current is only one-fifth the number of amperes as the primary. (Ignoring the loss of a certain amount of energy as heat.)

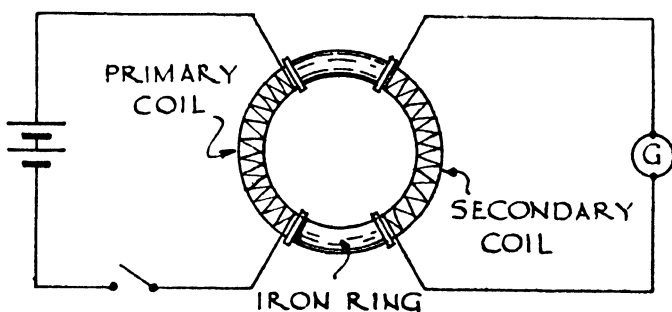


FIG. 430.—Principle of Electric Transformer.

From what has been stated as to the cause of the induced current it will be clear that the transformer can only be satisfactorily used to "step up" or "step down" current which is pulsating or *alternating*. The difference between this and the continuous or *direct* current with which we have hitherto dealt will be explained later.

**THE INDUCTION COIL.**—The induction coil is an arrangement for converting E.M.F. from a battery into pulsations of extremely high E.M.F., such as for the spark plug of an internal combustion engine. The primary E.M.F. of, say, 6-volts is stepped up to something like 10,000-volts. The primary circuit is similar to the electric bell circuit, with a few turns of comparatively thick wire wound around a core consisting of straight lengths of soft iron wire. The armature is mounted on a flat spring and oscillates between the pole of an electro-magnet and a contact screw when current passes through the primary circuit. The spring and screw are called the "make and break." The secondary coil is of many turns of thin wire wound directly on to the primary coil, but of course insulated from it. In operation there is an induced E.M.F. at "make" and another, in the opposite direction, at "break," as the suddenly

appearing and disappearing lines of force of the primary coil cut those of the secondary, the extremely rapid pulsation of high E.M.F. causing a spark to jump the gap at the plug. On large induction coils, made for special purposes, the wire of the secondary coil may be many miles in length.

**The Electric Generator.**—The principle of the generator or dynamo is that of Experiment 213, viz. the induction of E.M.F. in a conductor which is made to move in a magnetic field so as to cut the lines of force, so converting mechanical energy into electrical energy. Fig. 431 represents in cross-section a rectangular coil of conducting wire turning clockwise in the space between two magnet poles, *i.e.* in a magnetic field. The coil is cutting the lines of force and E.M.F. is thus induced in the coil, in this case in a direction anti-clockwise when viewed from above. The direction of the E.M.F. varies according to the direction of rotation in relation to the positions of the magnetic poles, thus :

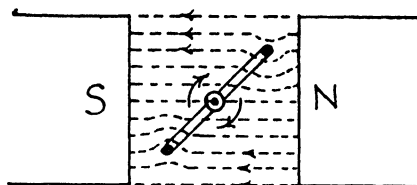


FIG. 431.—Principle of Electric Generator.

Rotation of Coil	Lines of Force	E.M.F. Direction (Plan)
Clockwise ..	R to L ..	Anti-clockwise
Clockwise ..	L to R ..	Clockwise
Anti-clockwise ..	R to L ..	Clockwise
Anti-clockwise ..	L to R ..	Anti-clockwise

**THE A.C. DYNAMO.**—The induced E.M.F. is clearly not constant but varies from maximum when the coil is horizontal to zero when the coil is vertical ; further, in each complete revolution the E.M.F. reaches maximum twice and zero twice—and *the two maximum surges of E.M.F. are in opposite directions* through the coil and therefore through any circuit connected to it. Fig. 432 gives a graphical representation of the

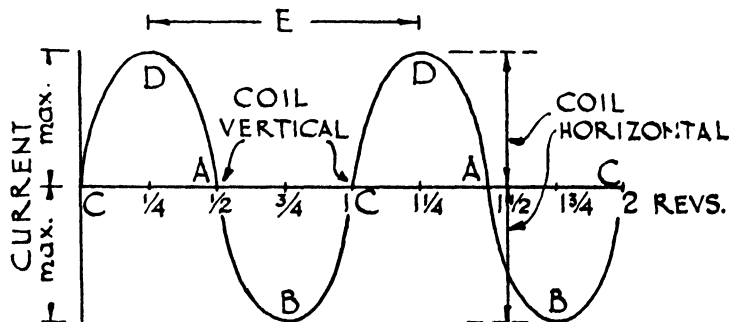


FIG. 432.—Alternating Current.

current we should obtain; it is called alternating current because its direction is repeatedly reversed, since the senses of the arrows indicating the linear direction of the current in opposite sides of the coil are opposite to each other. Fig. 433 shows how the current may be "collected" from the coil. A copper or brass slip ring is fixed to each end of the coil, rotating with it, and contact is made with these by fixed "brushes" consisting of springy strips of copper or small blocks of hard carbon. With a view to simplification of the diagram, bearings, etc. are not shown.

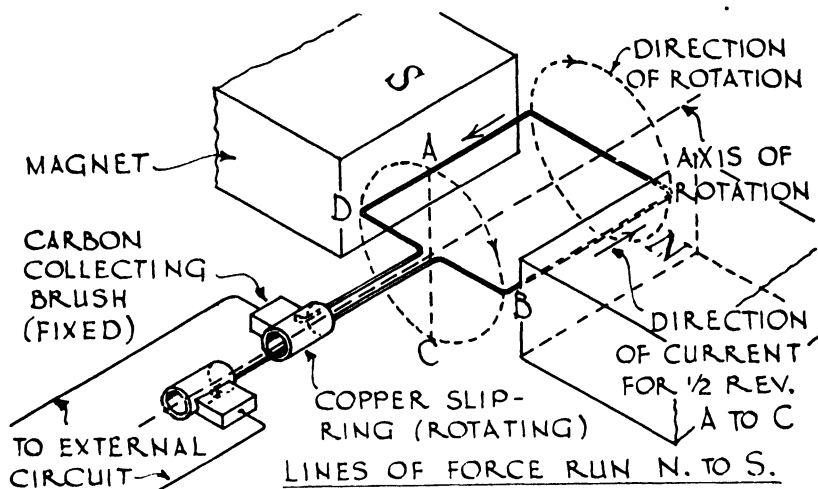


FIG. 433.—The Alternating-Current Dynamo.

The more rapid the rotation of the loop or coil the more rapid are the alternations of current, and the closer together horizontally the distance E in Fig. 432, but even at the highest practical speeds the flow of current from such a single loop would be far from smooth. In practice we therefore find that alternating current (A.C.) generators or *alternators* have an *armature* comprising a number of coils wound in different planes on to a soft iron core, and arranged so that their induced E.M.F.s are collected by a common brush or system of brushes. In addition a powerful electro-magnet is used instead of the permanent magnet, and in very large alternators the coils are wound on to a fixed central frame around which the electro-magnets rotate. There is thus no need for slip rings since the coils are stationary. A common *frequency* (of alternations of E.M.F.) is 50 cycles per second.

**THE D.C. DYNAMO.**—The principle is the same as that of the alternator, the difference lying in the method of "collecting" the current from the machine. Starting again with a single loop rotating in the magnetic field, compare Figs. 433 and 434. In the latter the two slip rings are replaced by a single ring made up of two sections insulated from

each other by mica or otherwise separated by being mounted on a roller of ebonite, etc. This is called a *commutator*, and in a practical machine it has many sections, in fact as many as there are coils in the armature.

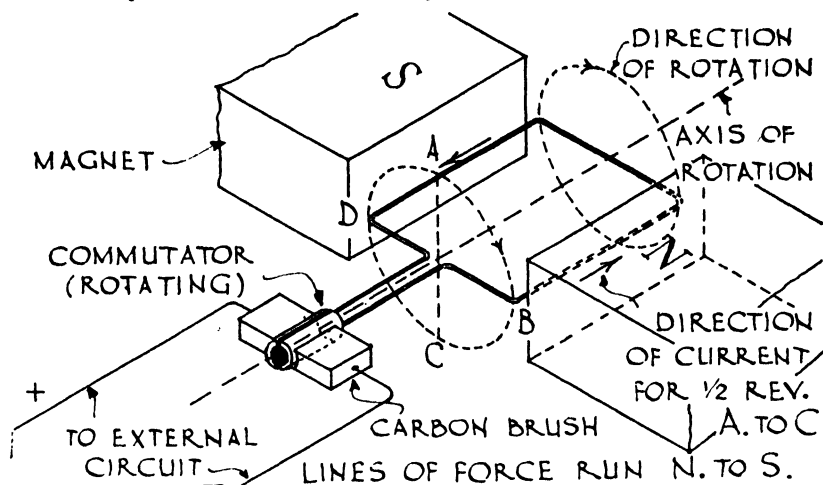


FIG. 434.—The Direct-Current Dynamo.

Now consider the rotation of the loop. Sides B and D are just cutting the lines of force across the axis of the poles and the surge of induced E.M.F. is at its maximum, but instead of B and D being of opposite signs as in Fig. 432 they are both the same, since by the time B has moved around to D the corresponding commutator section has moved around to the opposite collecting brush—and similarly with the other side of the loop. The graph, Fig. 435, shows the effect of this on the nature of the current, and

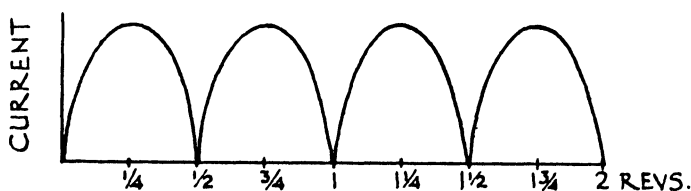


FIG. 435.—Effect of Commutator.

also serves to illustrate the fact that, although the current is now "direct," it is by no means continuously smooth. This is of course due to the elementary type of coil; the effect of the compound armature previously mentioned is that the flow of current is so smoothed out that in practice no pulsation is evident. As with the A.C. dynamo, electro-magnets are used to provide the strongest magnetic field.

The *field coils*, i.e. the windings of the electro-magnet, may be connected in one of two ways, "series" or "shunt." These are illustrated in Fig. 436. The E.M.F. is the same in both cases but each has certain

relative advantages which need not concern us here. It will be seen that in the series winding all the current passes through the field coils as well as through the external circuit, whilst with shunt winding there are two circuits, each taking part of the current.

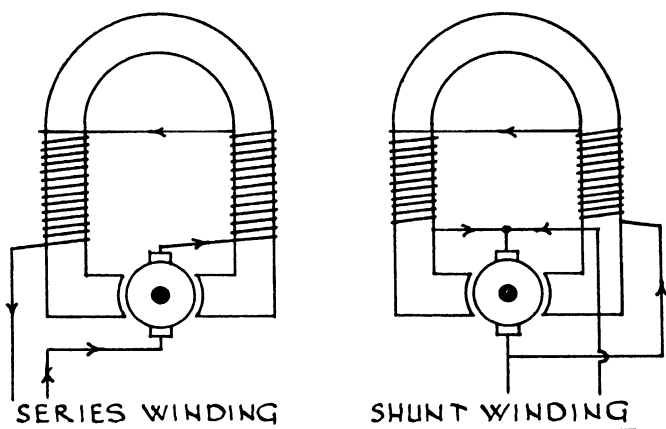


FIG. 436.—Methods of Winding.

For some purposes, such as for charging accumulators and in electrolysis, only direct current can be used, but alternating current is better suited to production and supply on a big scale, and can readily be converted into D.C. when necessary by *rectification*.

**The Electric Motor.**—The magnetic field due to a straight conductor carrying an electric current was investigated in Experiment 208. The field between two dissimilar permanent magnet poles is, along the width of the poles, uniform. These two magnetic fields are shown at A and B in Fig. 437, whilst at C is the combined field which would result from passing a current *downwards* through a straight wire between two magnets. In C the directions of the lines of force arising from the current and the magnet poles are opposite to each other "above" the wire, and the resultant field here is consequently weakened. "Below" the wire, however, they are in the same direction and reinforce each other, so resulting in a stronger field on this side of the wire. Now, lines of force can be imagined to act as elastic strings which, in similar circumstances, always tend to shorten to the minimum length. The net result of this weakening on one side and strengthening on the other is that the wire moves or tends to move towards the weaker side. When the current flows through the wire in an *upward* direction its field is anti-clockwise when viewed from above, and in this case the combined field is the reverse of that shown in Fig. 437 C, *i.e.* the weaker side is "below" the wire, and the wire tends to move in the opposite direction to that shown.



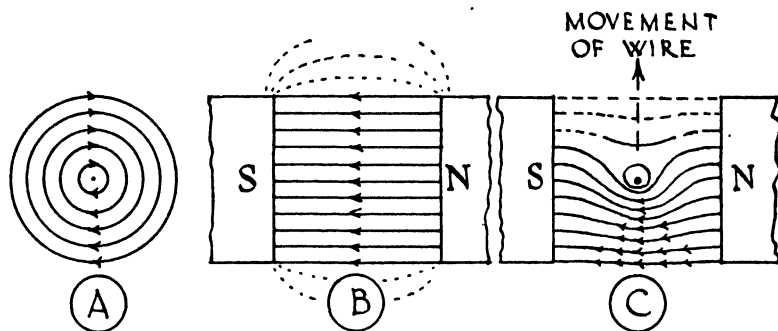


FIG. 437.—Effect of Current-Carrying Wire on Magnetic Field.

THE D.C. MOTOR.—Let us now consider, instead of a single wire, a loop such as in the simple D.C. generator. Instead of, as in Fig. 431, the loop being rotated in the magnetic field so as to induce E.M.F. in the loop, imagine the loop stationary and current passed through it. What happens will be clear from the previous paragraph; the two sides of the loop tend to move *in opposite directions*, and, given sufficient current in the loop and a sufficiently strong field, the loop rotates on its axis. Further, through the action of the commutator, the rotation continues so long as current is supplied. This arrangement is a simple D.C. motor but as before, in order to make practical use of it, the simple loop is replaced by an armature having many coils on an iron core and the field is greatly strengthened by passing some or all of the current through field coils on the magnet, according to whether series or shunt winding is adopted.

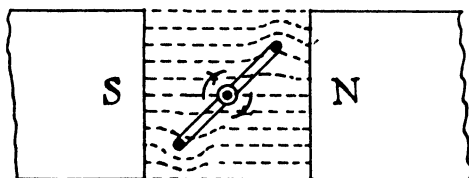


FIG. 438.—Principle of Electric Motor.

Again, referring to Fig. 438, it will be clear that the couple causing rotation is greatest when the loop is horizontal, and least (zero) when the loop is vertical. This would give an extremely irregular power output and is of course the reason for the employment of the multi-coil armature on the practical machine.

From the foregoing it will doubtless have been concluded that the D.C. dynamo and motor are really one and the same machine. This is true, the only difference in action being that their functions are reversed—in the dynamo electrical energy is produced from applied mechanical

energy, and in the motor mechanical energy is produced from applied electrical energy.

**A.C. MOTORS.**—The D.C. motor will run at any desired speed, but an A.C. motor (similar to the generator in Fig. 433) can obviously only work if its speed is “tuned in” to that of the generator supplying the alternating current. For instance, if the supply is 50 cycles per second the motor must be turned by outside power until a speed corresponding exactly to 50 cycles per second is reached, whereupon the motor itself responds and gives out power for so long as the current is supplied to it. If, however, the speed is allowed to drop to below the critical speed, such as by a temporary overload, the motor may “pull out of synchronism” and stop, and must then be re-started by outside power. It must therefore always be selected, as to size, to give plenty of reserve of power. This type of motor is called *synchronous* because its speed synchronizes with the frequency of the supply.

Another type of A.C. motor is the *induction motor*. This, briefly, works on the principle of Experiment 213, page 479. There we induced E.M.F. by the motion of an electrified coil inside a neutral coil, but in the induction motor this is reversed—we induce motion by means of an applied E.M.F. In practice such a motor comprises a stator and a rotor. The stator has a number of coils wound in slots around the inside of the casing, and through these the current is passed, so producing a revolving magnetic field. The rotor comprises an iron core through which are fixed a number of solid copper bars connected at their ends to copper rings. These tend to be drawn around by the encircling field.

#### 4. MEASURING INSTRUMENTS.

It is proposed now to describe briefly some of the instruments which we have used for indicating or measuring electrical quantities, as we are now in a position to understand their working. The majority of such instruments depend for their action upon the magnetic effect of electric current, but a notable exception is the “hot wire” type which makes use of the temperature movement of a wire due to the heating effect of the current.

**THE HOT WIRE INSTRUMENT.**—This is shown diagrammatically in Fig. 439. The current flows mainly through the thicker shunt wire without affecting the pointer, but a pre-determined portion passes through the thinner and longer “hot” wire. To this latter is attached a non-conducting thread fixed at its other end to a spring, and intermediately passing around a small pulley supporting the pointer. As a result of the expansion of the hot wire the spring pulls the thread and in doing so the pulley is rotated and the pointer moved across the scale.

**THE MOVING COIL INSTRUMENT.**—This works on the principle of the motor, *i.e.* the turning effect exerted upon a loop or coil carrying a current and placed in a magnetic field. In Fig. 440 the coil is free to rotate in the space between a fixed cylindrical iron core and the shaped poles of a permanent magnet. The core is disconnected magnetically from the magnet by brass bridging pieces. The two ends of the coil are attached to spiral springs through which the current is led, and on the common spindle is a pointer. The rotation of the coil and pointer is accurately balanced by the two springs.

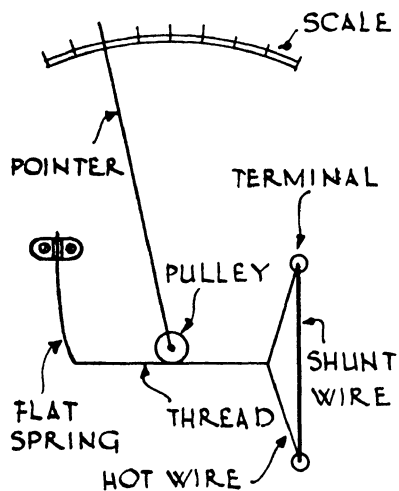


FIG. 439.—The Hot-Wire Measuring Instrument.

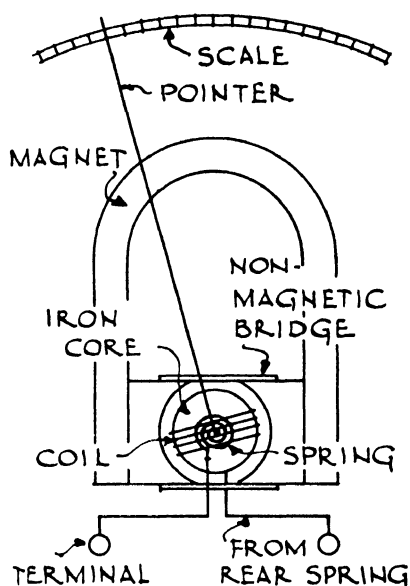


FIG. 440.—The Moving-Coil Measuring Instrument.

**THE MOVING IRON INSTRUMENT.**—The principle of this instrument is that of EXPERIMENT 211, page 476, in which a piece of iron is attracted or repelled by being placed in the field of a solenoid. Fig. 441 illustrates this in a simple way. The soft iron is mounted on the end of a pointer carried on a spindle and governed by a pair of springs (not shown).

A more usual type depends upon the mutual repulsion of two like poles, the poles being pieces of iron both magnetized by the solenoid carrying the current to be measured. One of the pieces of iron, A in Fig. 442, is fixed to the solenoid reel, the other, B, being attached to the pointer. Upon the current passing through the coil A and B are magnetized with the same polarity and repel each other, but as A is fixed B moves and so rotates the pointer. A spiral spring (or sometimes two springs with their turns in opposite directions) restores the pointer to zero.

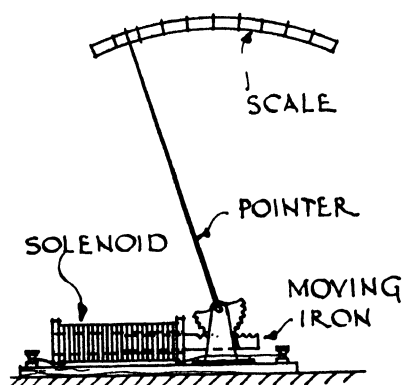


FIG. 441.—Principle of the Moving-Iron Instrument.

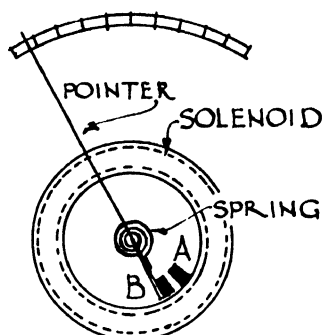


FIG. 442.—The Moving-Iron Measuring Instrument.

**USE OF INSTRUMENTS.**—These types of instrument may, with the necessary modifications, be used as galvanometer, ammeter or voltmeter, the scale being calibrated accordingly.

The galvanometer may be based upon the principle of Experiment 206 (page 471) but with its sensitivity increased by employing many turns of wire instead of a single length. Its use is mainly to detect and compare weak currents. The moving coil instrument is also suitable for use as a galvanometer because of the delicate balance of its moving parts. In fact it is suitable for taking directly a maximum current of only about  $\frac{1}{20}$  ampere, or 50 milliamps, unless modified, whilst it is possible by means of a special kind of suspension of the coil to make the instrument sensitive to less than  $\frac{1}{2}$  milliamp. Instead of pointer and scale the galvanometer is often arranged with a small mirror attached to the moving part. A pencil of light directed on to this is then reflected on to a long scale, so giving great magnification and enabling scarcely perceptible actual movement to be detected with ease. One such instrument used by the writer gives a deflection of 20 cm. per micro-amp.

The ammeter is a low-resistance instrument placed in series in a circuit for the purpose of measuring the strength of the current. The whole of the current therefore passes through it. All three types of instrument are used but the scale is calibrated according to the range of current strength for which it is to be employed. For strong currents (for the ammeter rather than the milli-ammeter) a resistance of *low* value is connected *in parallel* with the instrument and the scale modified in accordance. On the hot wire instrument the shunt wire fulfils this function and it is selected according to the resistance required.

The voltmeter is a high-resistance instrument, and is connected in parallel in a circuit—so as merely to bypass some of the current whilst

measuring the E.M.F. The instrument, of whatever type, is made to act as a voltmeter by connecting a *high resistance in series* with it, with suitable modification of the scale. An instrument intended to be used solely as a voltmeter has this resistance incorporated, but otherwise a milliammeter and a separate resistance are connected in series and the E.M.F. found from the measured current (amps.) and resistance (ohms).

The moving iron and hot wire instruments may be used with either direct or alternating current.

## 5. ELECTRICAL POWER AND ENERGY.

Power has been explained in Chapter XVIII as the rate of doing work, the unit of power, the *horse-power*, being 33,000-ft.-lb. of work per minute, or 550-ft.-lb. per second. The electrical unit of work being the *joule* (see page 469), the electrical unit of power is the *joule per second*. This is usually referred to as the *watt*, and as a current flowing at the rate of 1 coulomb per second is 1 *ampere* we may say :—

1 joule per second is the power represented by 1 amp at 1 volt or  
watts = amperes  $\times$  volts.

It may be shown that 1 horse-power is the equivalent of 746 watts ; the watt is therefore a very small unit for practical use, and the *kilowatt* (1,000 watts) is used also. It should be remembered that the watt and kilowatt are units of *power*. The corresponding units of *energy* are the *watt-hour* (1 watt over a period of 1 hour—or 3,600 joules) and the *kilowatt-hour* (1,000 watt-hours—or 3,600,000 joules). The kilowatt-hour is the unit by which electrical energy is purchased, and is often called the *Board of Trade Unit* or B.T.U. As was stated when dealing with the British Thermal Unit (B.Th.U.) this similarity is liable to lead to confusion, and to prevent this a more recent designation is *B.O.T. unit*. In everyday parlance it is termed merely the *unit* of electricity.

EXAMPLE.—An electric heater takes a current of 4 amps. and its resistance is 60 ohms.

Calculate :—

(a) The energy consumed if it is used for 50 hours.

(b) The heat generated in 1 hour.

Power of heater = 4<sup>2</sup> amps.  $\times$  60 ohms. = 960 watts.

(a) Energy consumed in 50 hours = 960 watts  $\times$  50 hours.  
= 48,000 watt-hours  
= 48 kilowatts or "units."

(b) Heat generated = 960 watts  $\times$  3,600 joules (per hour)  
=  $\frac{960 \times 3,600}{4.2}$  = 822,857 calories  
= 3262.7 B.Th.U.

DISTRIBUTION OF ELECTRICITY.—Electrical energy in quantity, such as a public supply, is invariably provided by generators. The power used to drive them varies according to circumstances.

In some parts water power is available and apart from the high initial cost of the installation this gives the cheapest supply. Such "hydro-electric" plants depend upon a plentiful and constant supply of water with adequate head and capable of being led directly to the power plant, usually water turbines. These are of two principal kinds, the "reaction" type, which has curved fins set obliquely on a wheel arranged with its axle in line with the direction of the water, and the "impulse-wheel" type, in which a large number of cup-shaped vanes are set around the rim of a large wheel set with its axle at right-angles to the direction of the water. The reaction type is suitable for use with a large flow of water at low head (a head of 2 ft. will give 1 h.p. but requires a flow of 360 c.ft. per minute). The impulse-wheel turbine requires a small flow at high pressure (a head of 40 ft. gives 1 h.p. but only takes 17 c.ft. per minute).

In this country there are very few water-powered plants on a large scale, but owing to the plentiful coal supply steam power provides an alternative means of obtaining electrical energy in large quantities at low cost. Nearly all of our power stations use coal-fired steam power. In such a plant the potential chemical energy of the coal is converted into heat which turns water in the boilers into steam, this producing mechanical energy in the steam turbine to which the generator is coupled. The final stage is the conversion of mechanical energy into electrical energy by the generator, and upon tapping the supply the user re-converts this according to his needs.

Although there are still many independent electricity supply undertakings they are gradually being joined to the national scheme of supply. Under this scheme the whole of England, Scotland and Wales is covered by a network of transmission lines supplied by many generating stations. The current is A.C., largely because of transmission problems—a heavy current requires extremely thick and expensive wires, so that for the purpose of transmission it is changed into a smaller current at higher voltage. In the primary network or "grid" the pressure is stepped up by transformers at the generating stations before being "pumped" into the lines at 132,000-volts. This pressure or potential difference has to be maintained continuously between any pair of the primary lines. Subsidiary to the main grid network are many district networks supplied from the grid at a lower voltage by stepping down to 66,000-volts, and in some cases to 33,000-volts. These secondary networks carry the supply to districts distant from a main grid route, and such districts have transforming stations instead of generating stations. Further networks to cover areas are supplied from this system, the voltage being again stepped down to 11,000, 6,600 and 3,300 volts according to requirements. All such networks are called "transmission" systems, whilst the further distribution lines throughout a town or village are called "distribution"

systems. The final voltage as it reaches the consumer is 400 volts for industrial and 230 volts for domestic use. As has been stated on page 481, this convenient stepping up and down of the current would be impracticable with D.C.

### Exercises.

1. Calculate the quantity of electricity (in coulombs and ampere-hours) represented by a current of 30 amperes maintained over a period of 2 hours.  
(Ans. 216,000 coulombs. 60 ampere-hours.)
2. A current of 3 amperes is passed through a copper voltameter for 1 hour. What weight of copper is deposited ?  
(Ans. 3.56 gm.)
3. An electric heater takes a current of 3.5 amperes and its resistance is 60 ohms. What is its power, and what heat energy (in B.Th.U.) does it generate in 30 minutes ?  
(Ans. Power = 735 watts.  
Heat generated = 1,250 B.Th.U.)
4. An electric heating appliance of 600 watts is connected to a supply of 230 volts. What current does it take, and what is its resistance ?  
(Ans. Current = 2.61 amperes.  
Resistance = 88 ohms.)
5. What is the power of an electric lamp which takes .435 amperes when connected to a 230-volt supply ?  
(Ans. 100 watt.)
6. It is required to make a new heating element for a 2-kilo-watt electric fire to be used on a 230-volt supply. A length of 1 yard of the wire available is tested by being connected in series with a cell and an ammeter, the voltage being 2 and the ammeter reading .8 amperes. How many yards of the wire are required ?  
(Ans.  $10\frac{1}{2}$  yards.)

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